Very-high energy gamma-ray emission of the Galactic Center and Inner Galaxy

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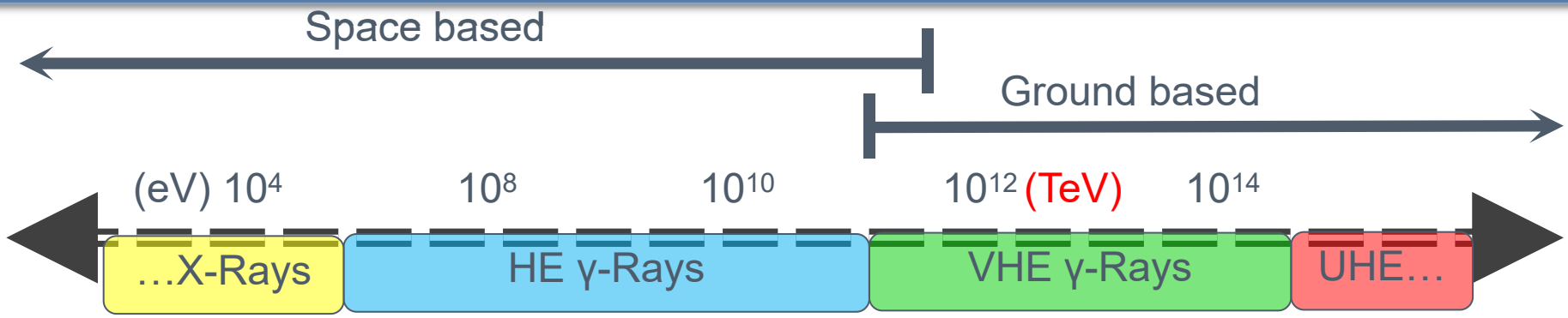
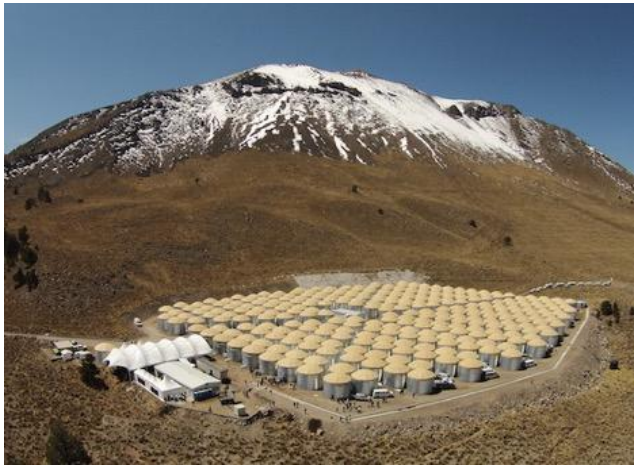
The extreme electromagnetic universe



Gamma-ray satellites:
- EGRET
- Fermi-LAT

Imaging Atmospheric Cherenkov Telescopes (IACT) and Water Cherenkov



The current IACT world

VERITAS Arizona, USA
1275m a.s.l.
4 telescopes, Ø12m
Stereoscopy
>2007

MAGIC Canary Island, Spain
La Palma, 2225m a.s.l.
2 telescopes, Ø17m
>2009

H.E.S.S. Namibia
1800m a.s.l.
4 telescopes, Ø12m
stereoscopy
>2003
HESS 2 : 4+ 1 (Ø28m) telescopes, 2012

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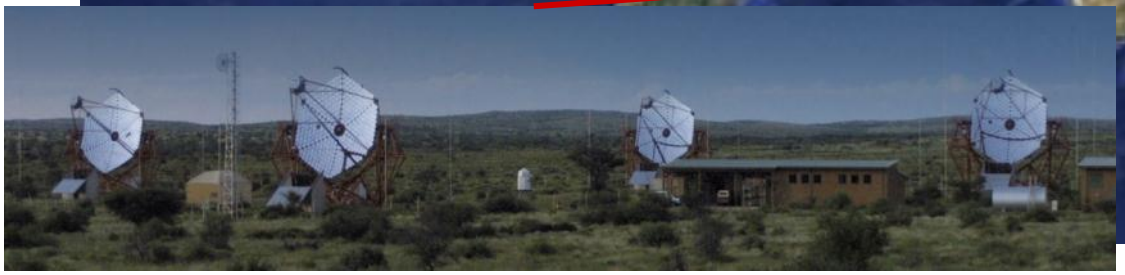
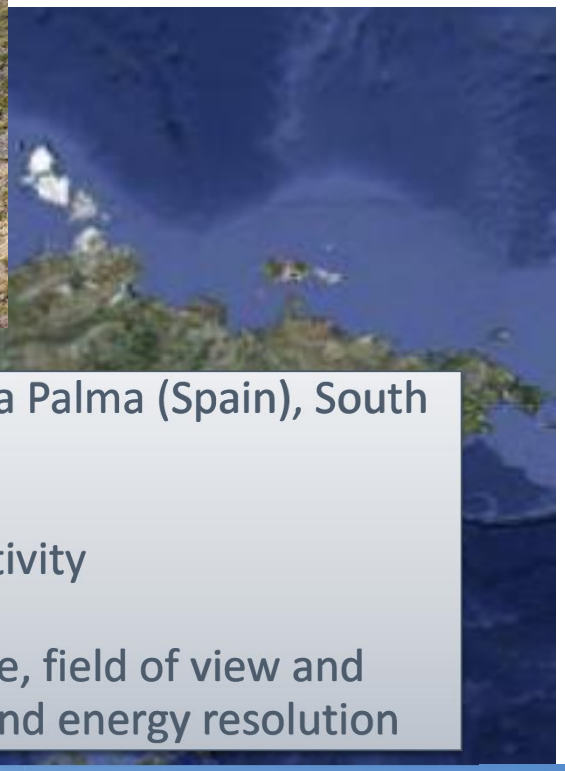
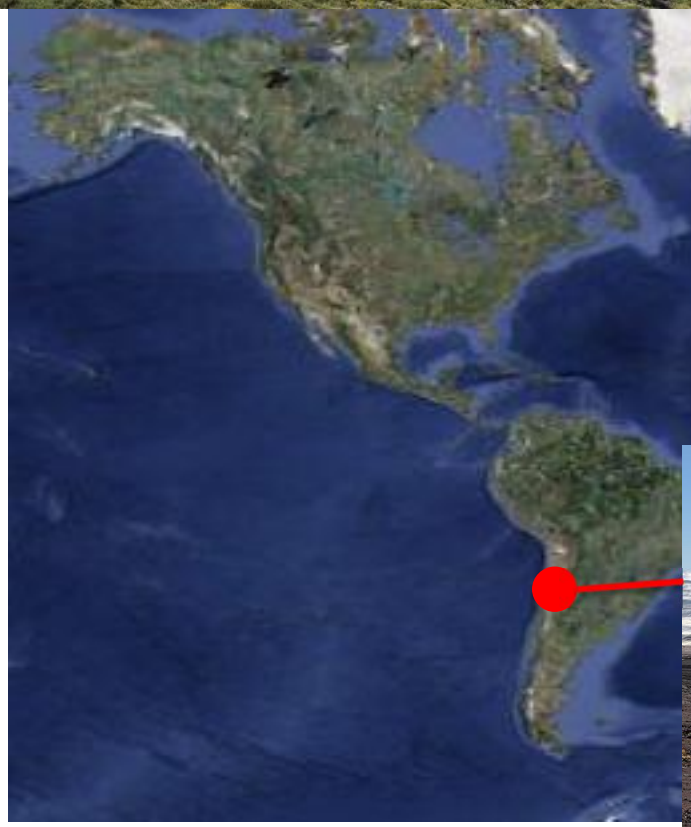


H.E.S.S. Namibia

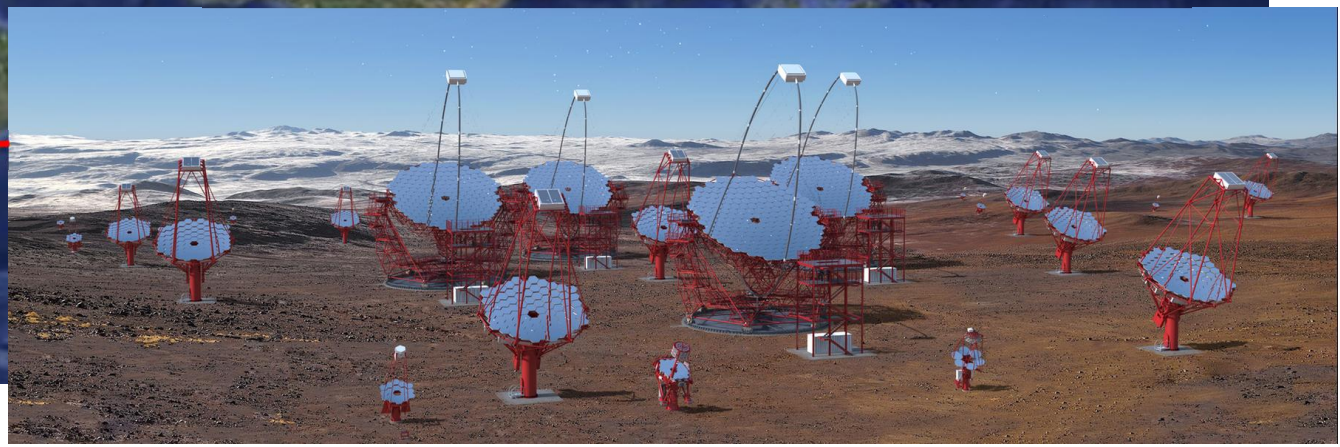
- Geographically best suited for the Galactic Center observation
- The only IACT with a constant monitoring of the GC
- Now more than 220h with very precise measurements (spectrum and position)

The future of gamma-ray telescopes: Cherenkov Telescope Array





- Two arrays: North in La Palma (Spain), South in Paranal (Chile)
- Factor 10 better sensitivity
- Larger energy coverage, field of view and twice better angular and energy resolution



The H.E.S.S. telescope array
H.E.S.S.-phase 1: 2003-2012

Array of four Imaging Atmospheric Cherenkov Telescopes

located in Namibia (1800m a.s.l.)

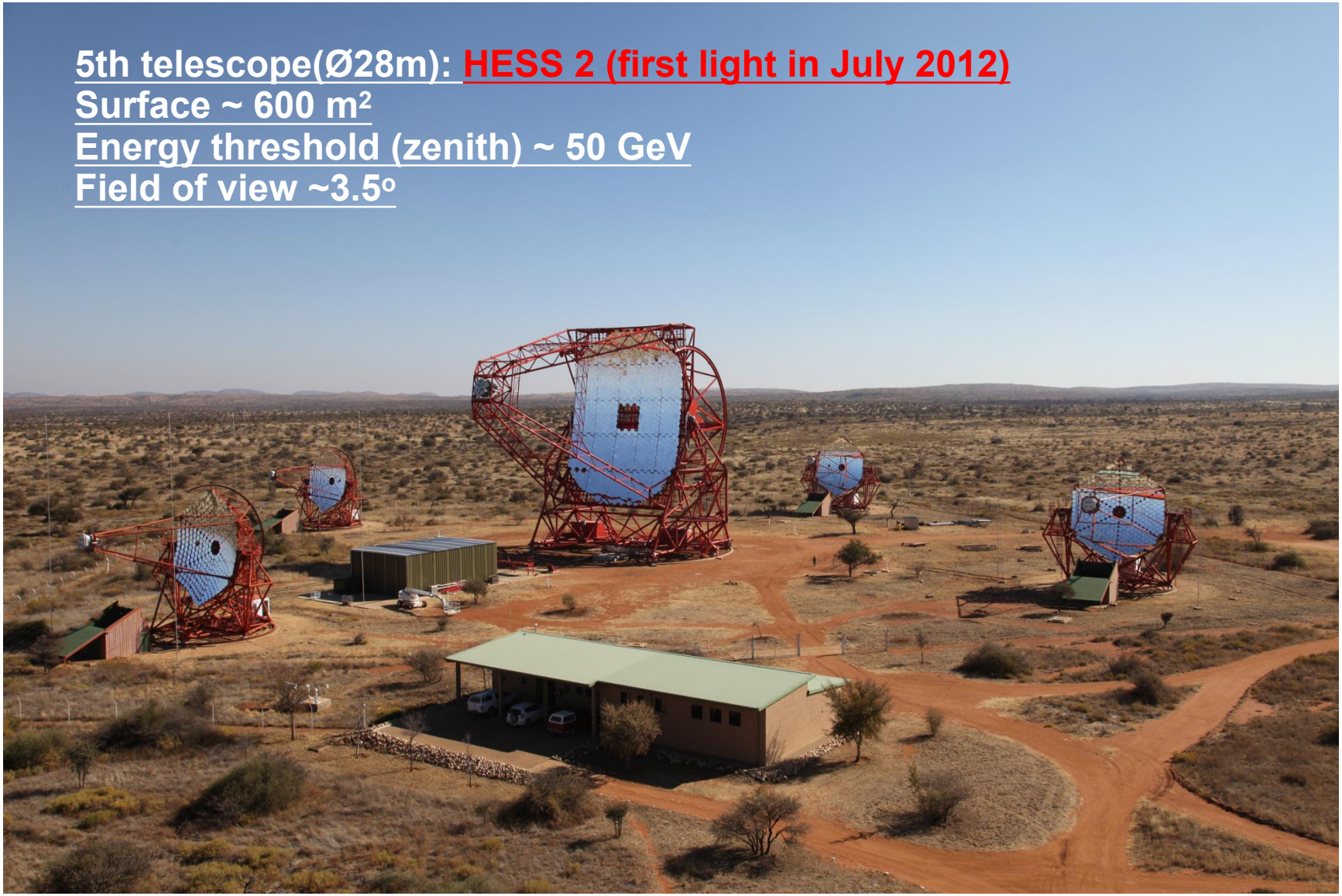
- 12 m diameter telescopes : 107 m^2 each
- Observations on moonless nights, ~1000h/year
- Field of view of 5° in diameter
- Stereoscopic reconstruction

- Angular resolution < 0.1°/γ
- Energy threshold (zenith) ~ 200 GeV
- Energy resolution ~ 15%

The H.E.S.S. telescope array
H.E.S.S.-phase 2: 2012

Array of FIVE Imaging Atmospheric Cherenkov Telescopes

located in Namibia (1800m a.s.l.)



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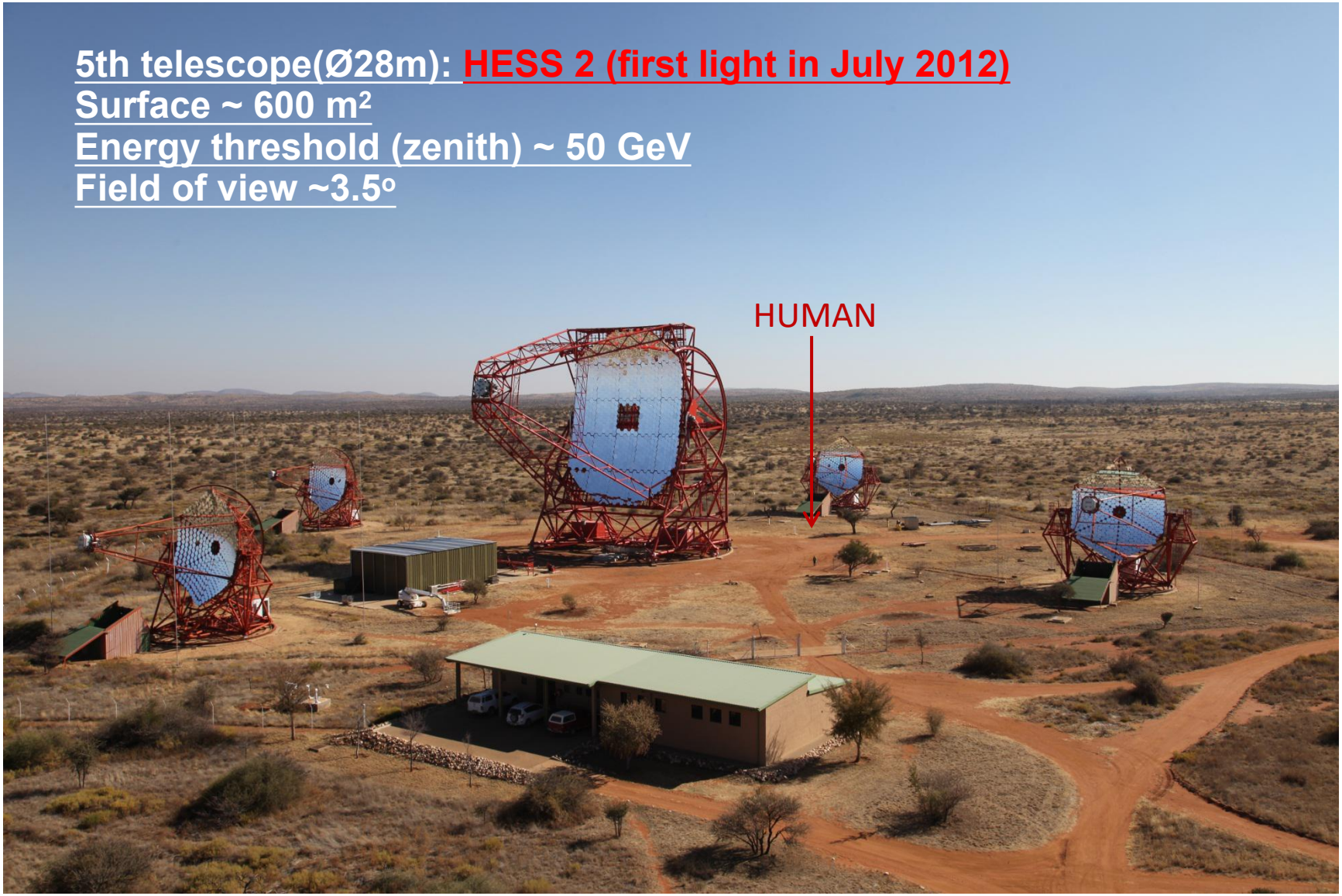
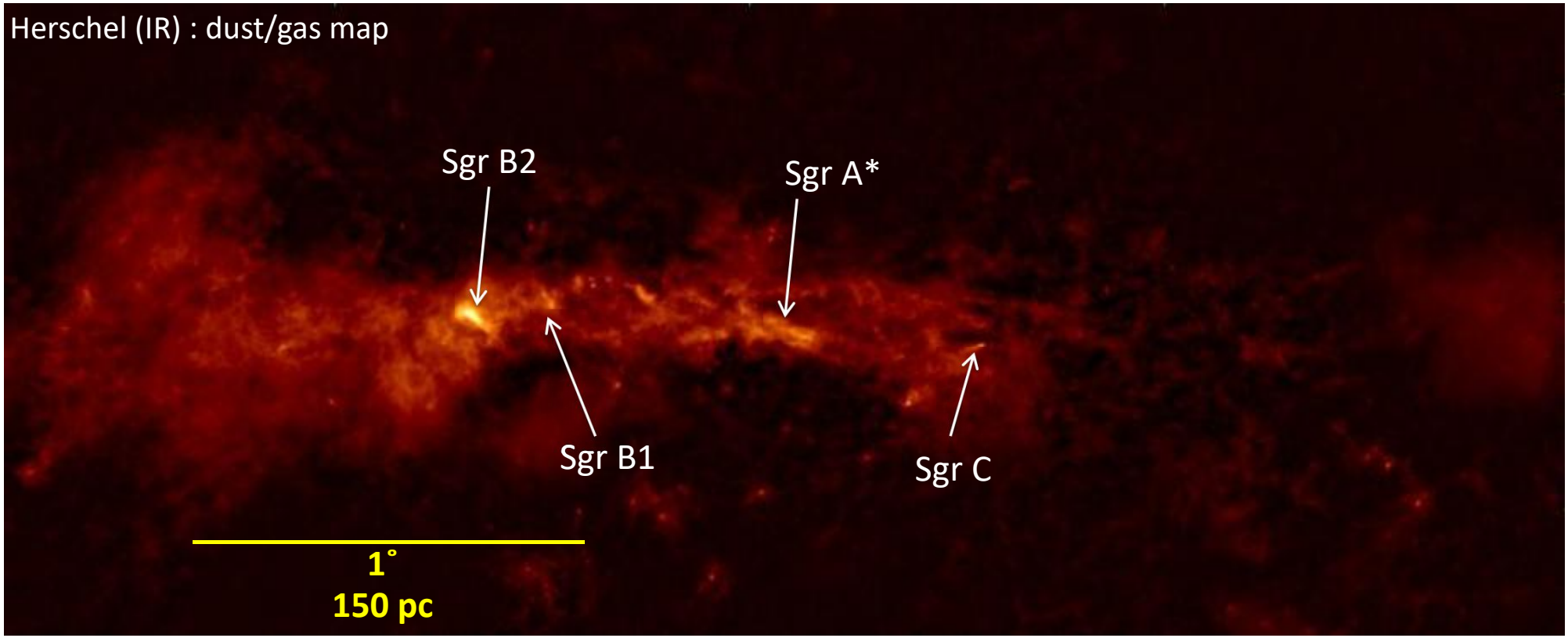


The Galactic Center region

- Central Molecular Zone (CMZ): giant molecular clouds (~10% of all Galaxy)



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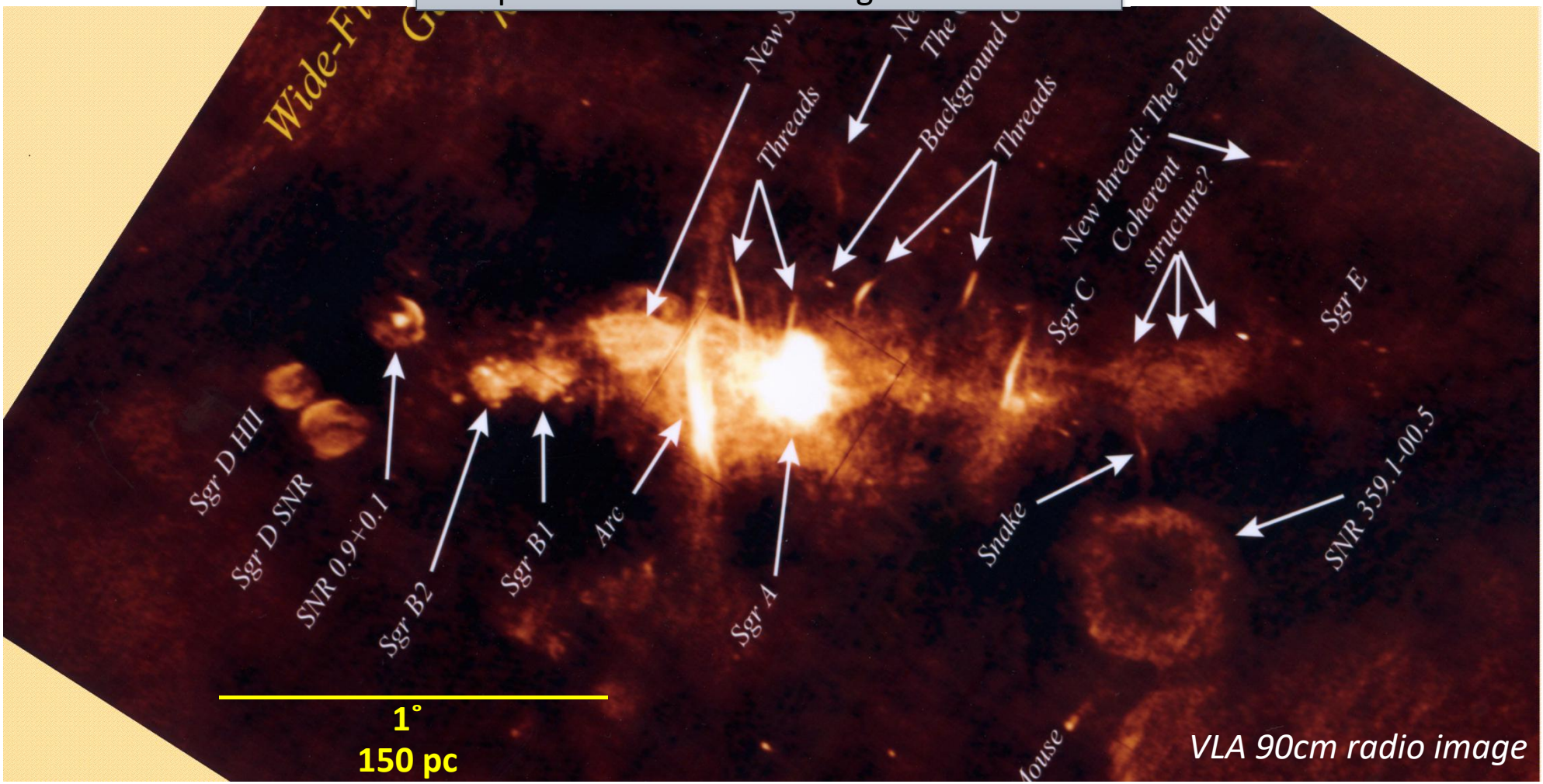
- CR accelerators: SNRs, magnetic filaments, supermassive black hole Sgr A*

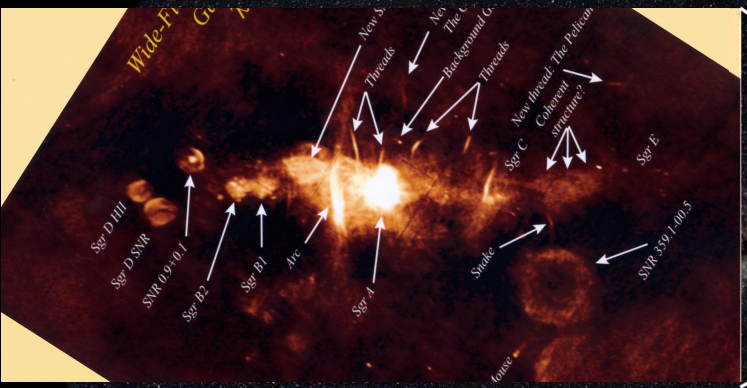


Past activities of the Galactic Center

> 10^5 years timescale

Radio emission -> Huge ouflow (10^{39-41} ergs/s)

8 kpc



Carretti et al, Nature 2013

Past activities of the Galactic Center

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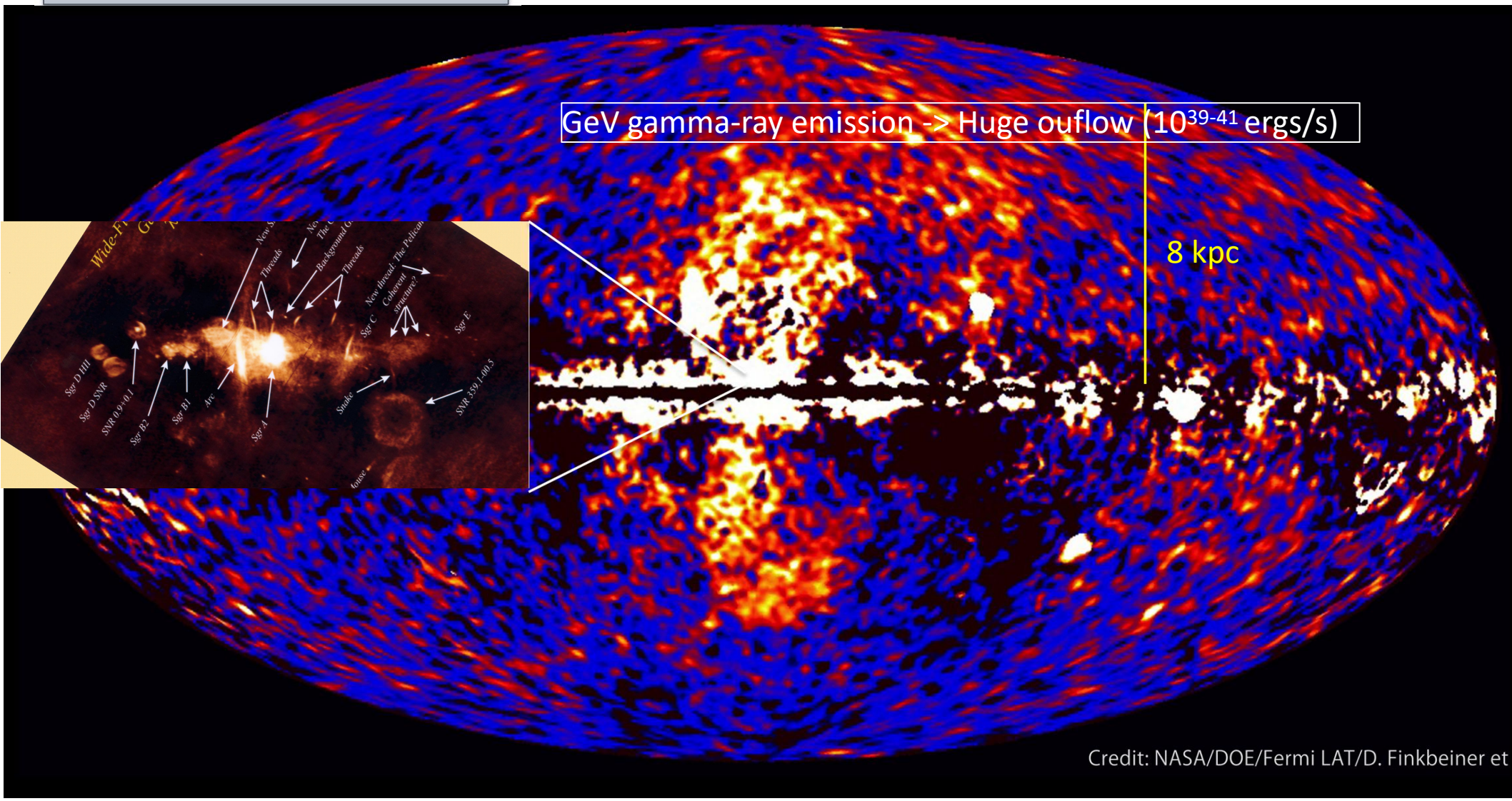

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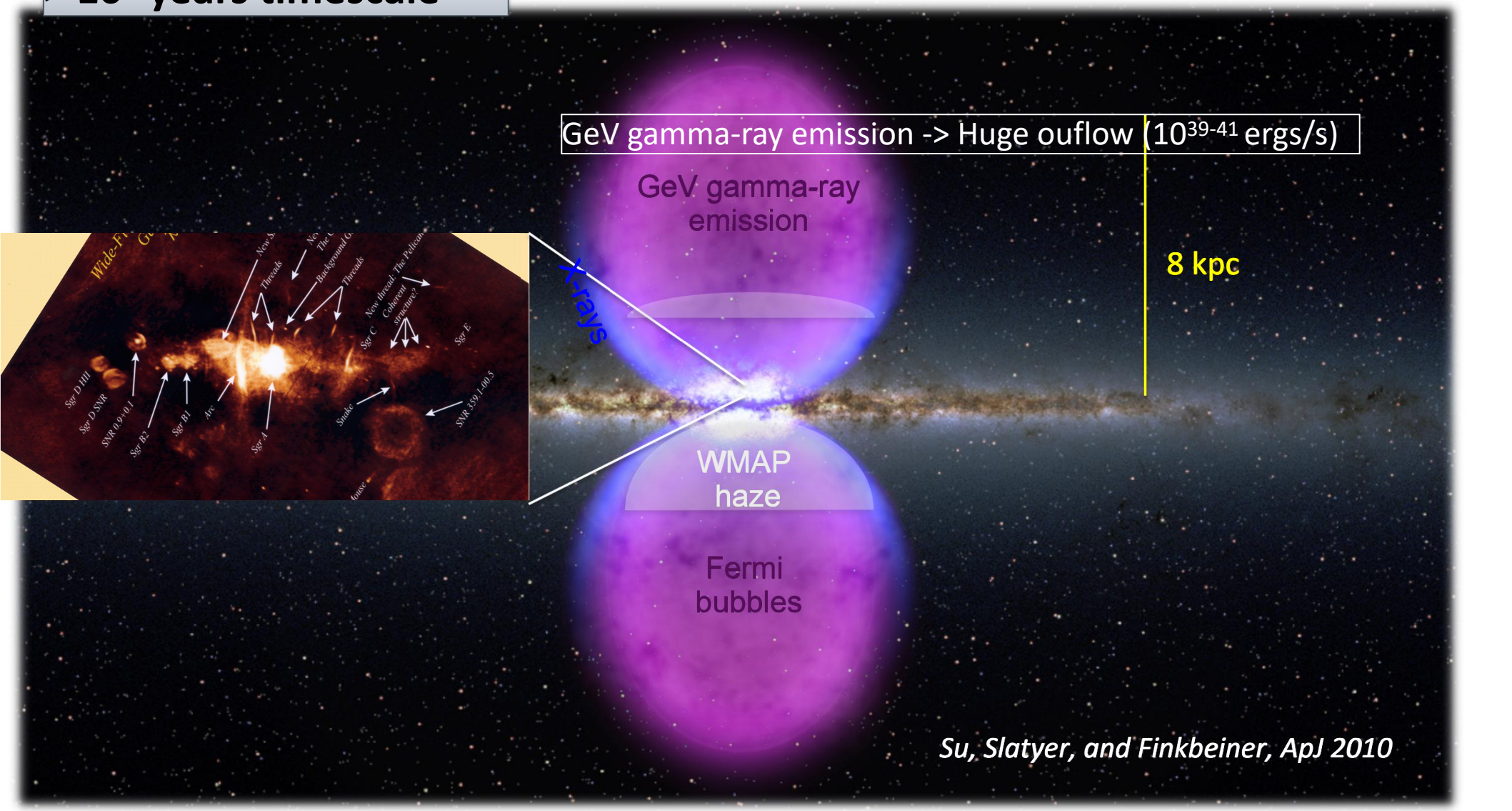
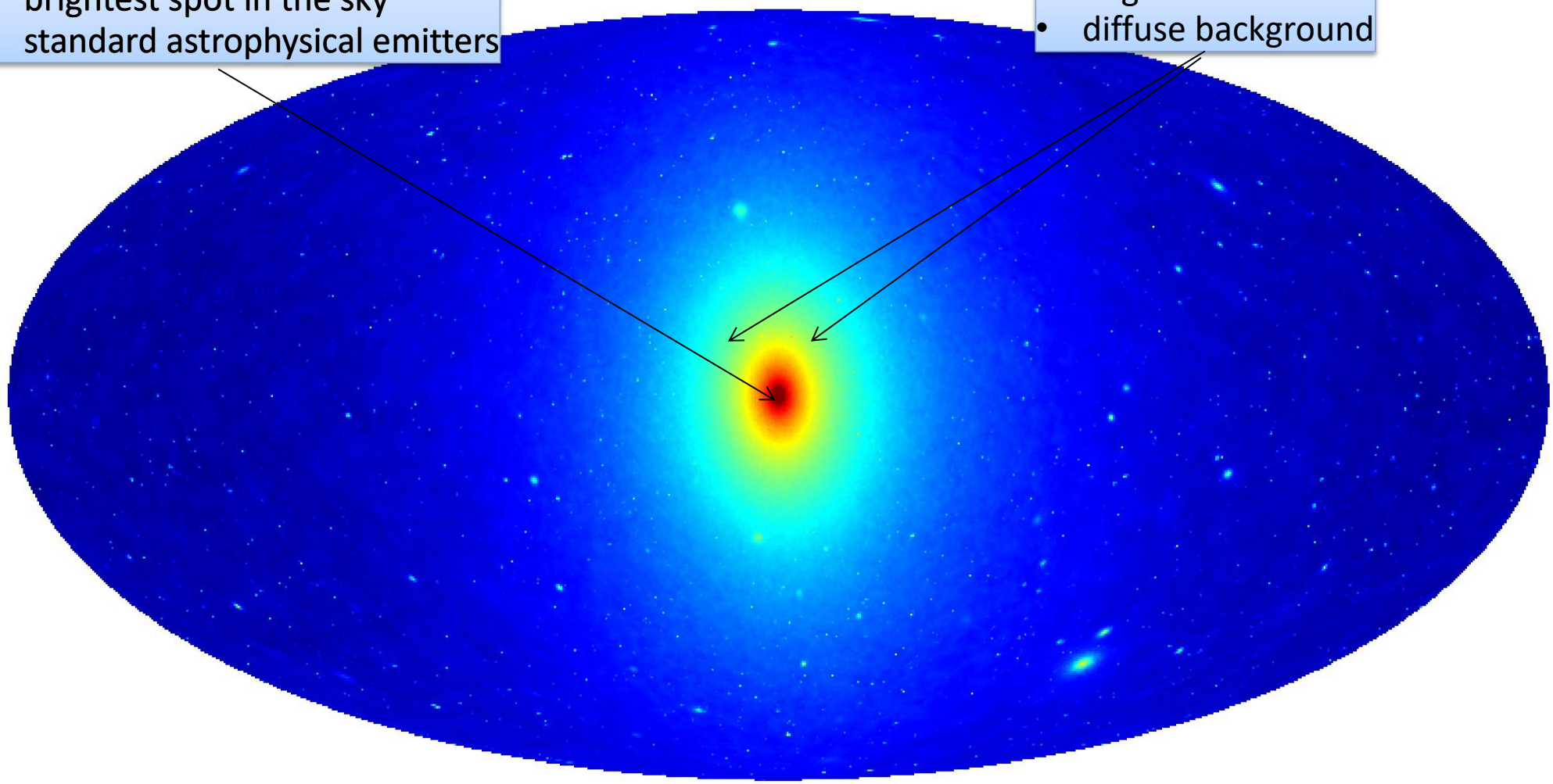


Dark Matter annihilation in the Galactic Center

Galactic Center
- brightest spot in the sky
- standard astrophysical emitters

Galactic Halo
- large statistics
- diffuse background



Aquarius simulation
Springel et al 2008

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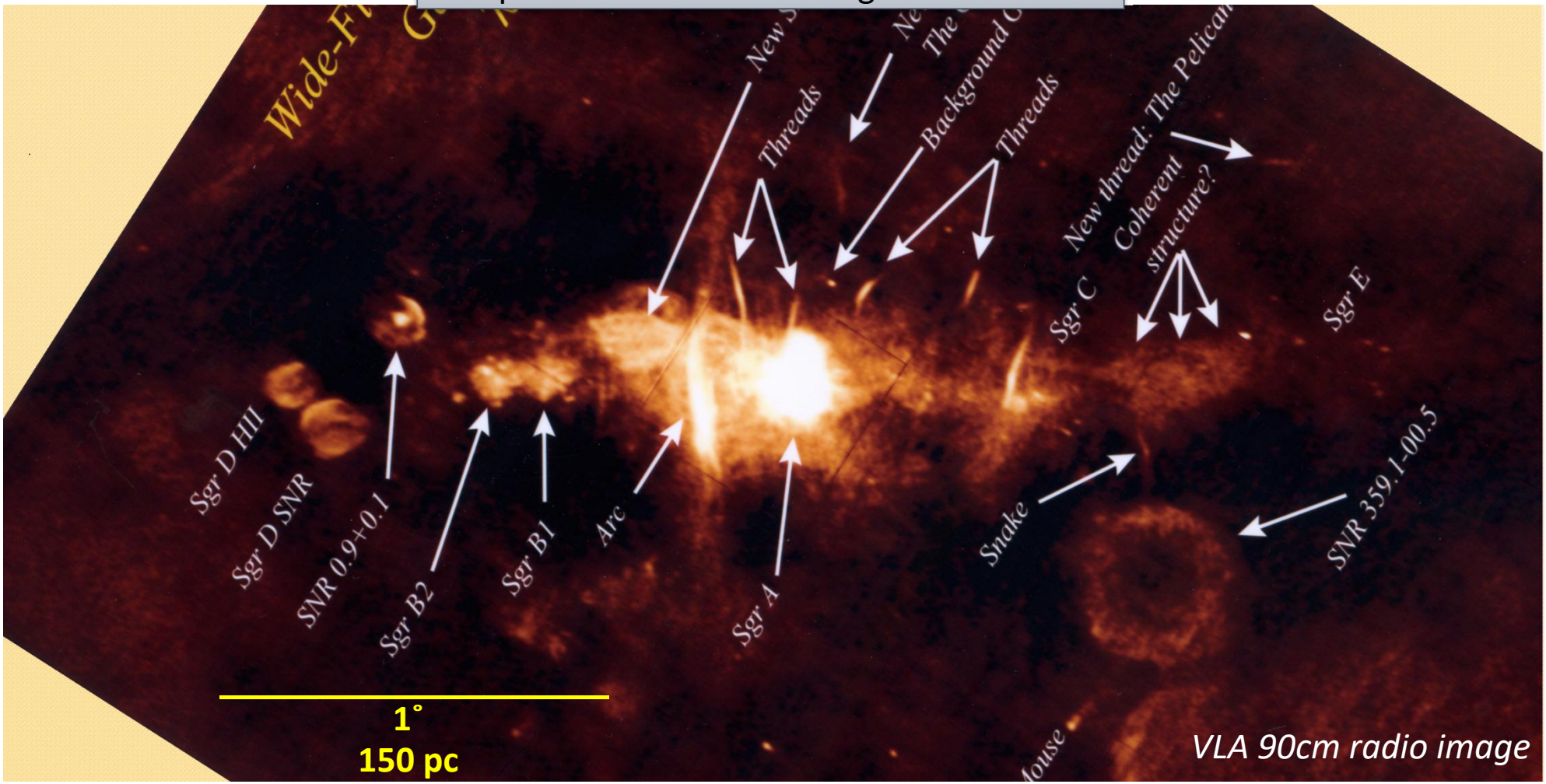
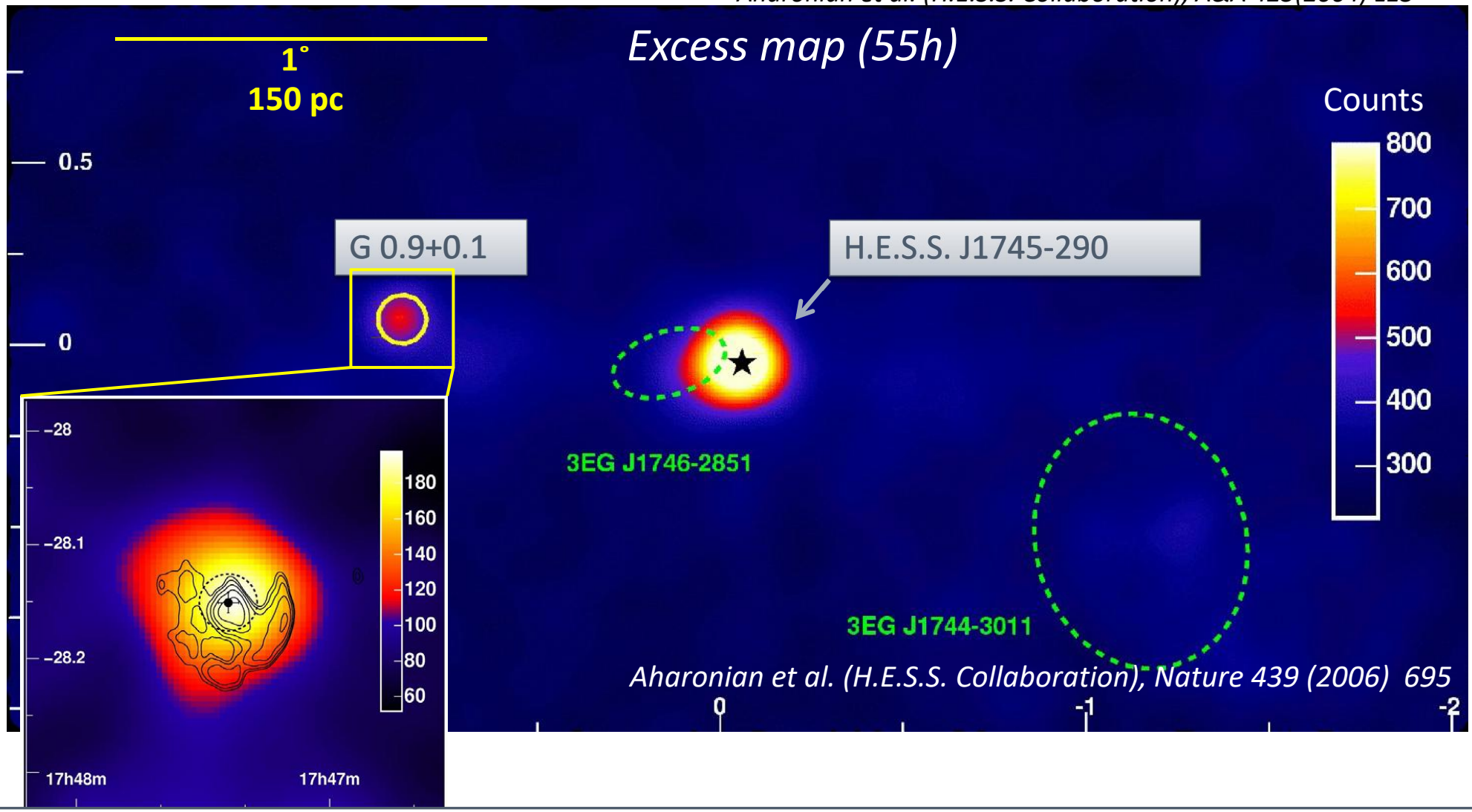


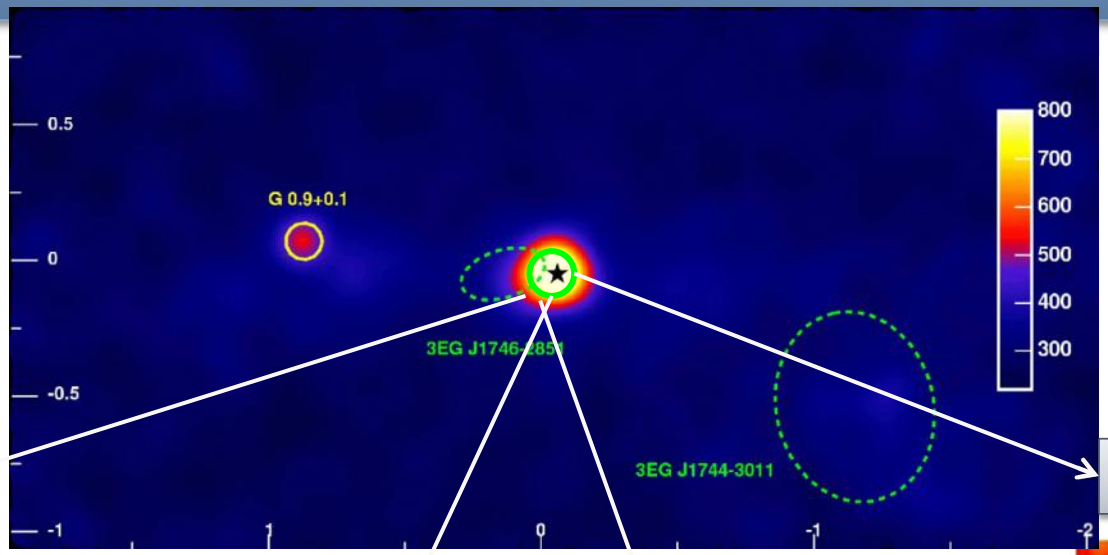
The Galactic Center region in gamma-rays: H.E.S.S. 2003-2005

Two bright point-like sources:
- G 0.9+0.1 : SNR/PWN association
-HESS J1745-290 : unidentified source

Aharonian et al. (H.E.S.S. Collaboration), A&A 425(2004) L13

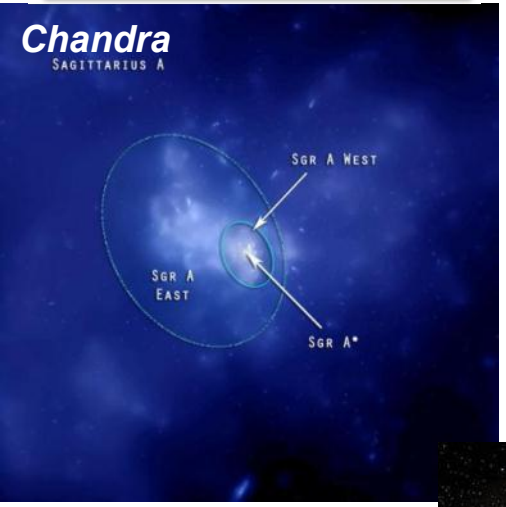


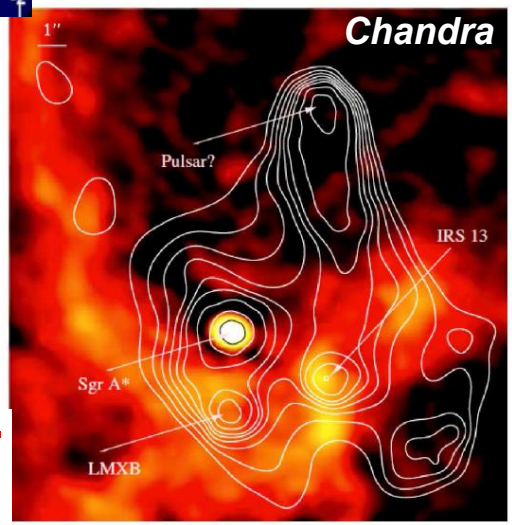
Which are the possible counterparts for HESS J1745-290?



SNR Sgr A East

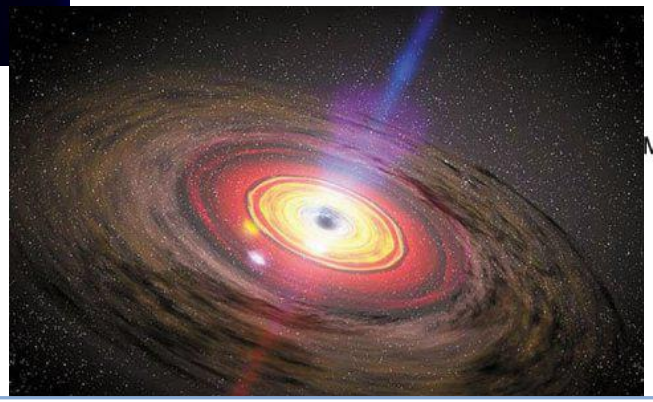
PWN G359.95-0.04

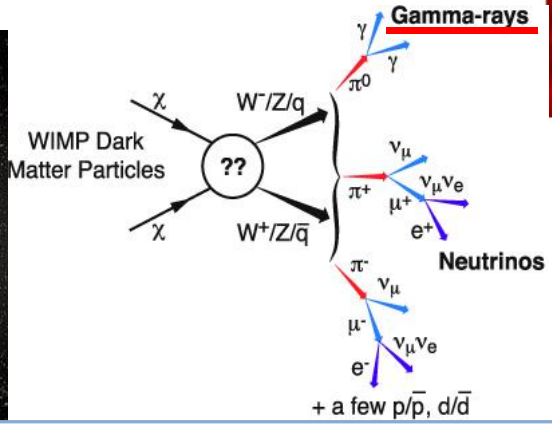




SMBH Sgr A*

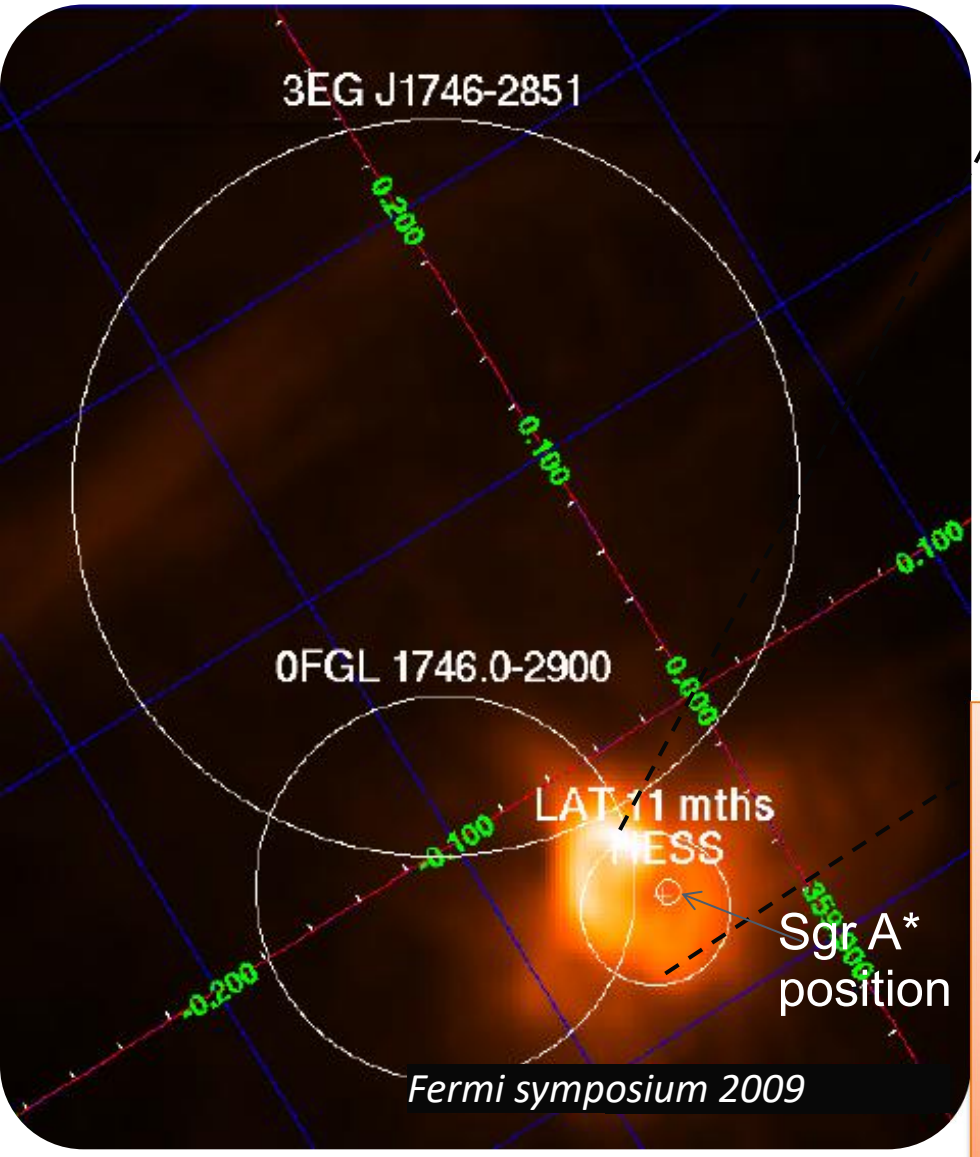
Dark Matter?

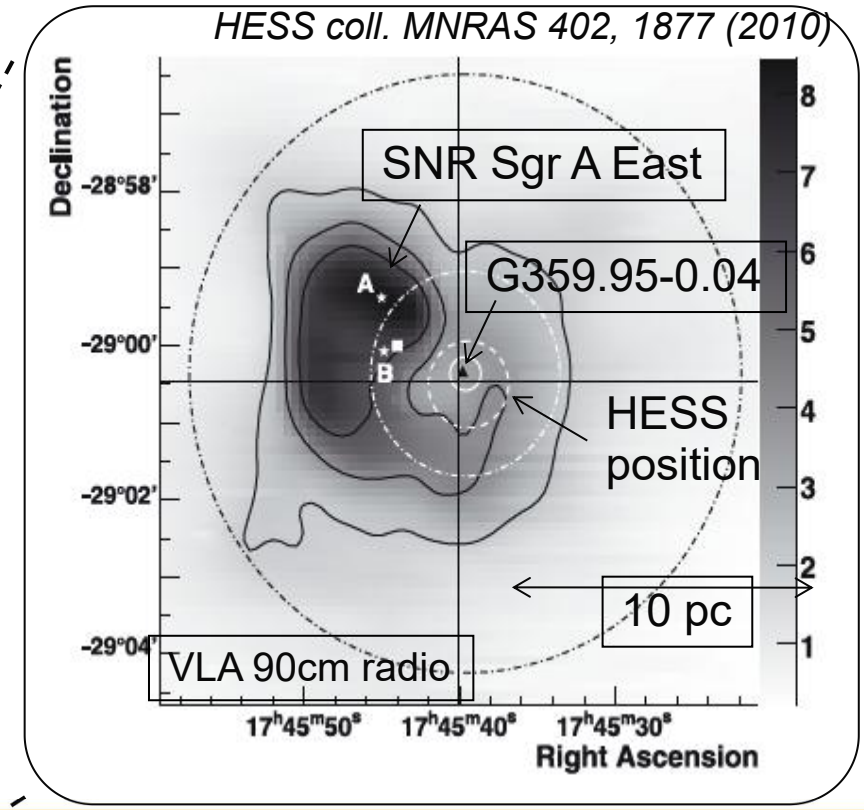




The HESS J1745-290 central source position

HESS improved pointing analysis : 30''->6''





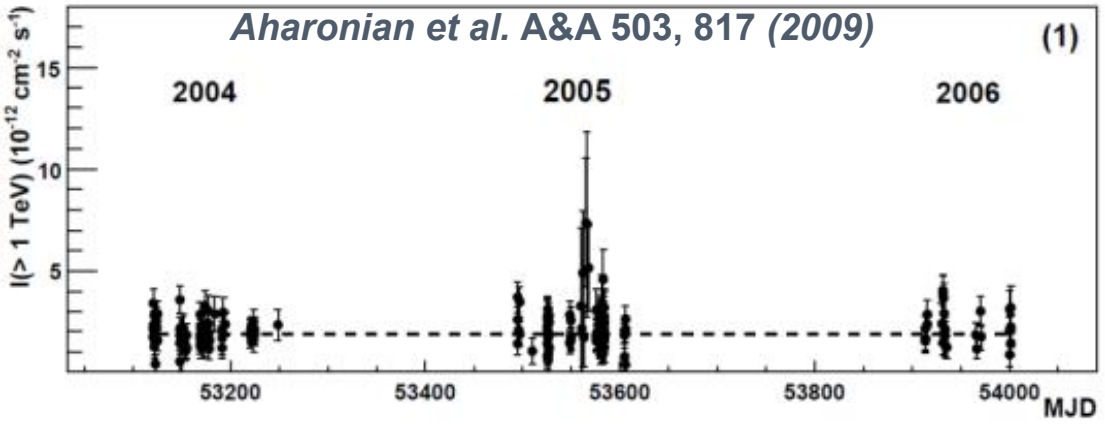
- position:
  l=359° 56'41.1'' ± 6.4'' ± 6''
  b=-0° 2'39.2'' ± 5.9'' ±6''
- centroid emission located at 7'' ±12'' from Sgr A*
- Sgr A East excluded at the 7s C.L.
- G359.95-0.04 and Srg A* still inside error bars (8.7'' from Sgr A*)

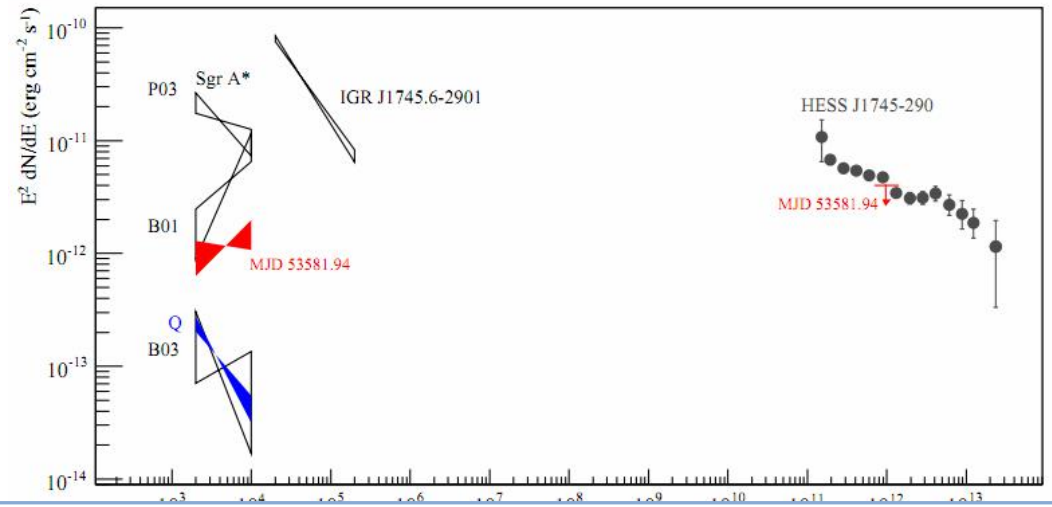
The GC central source (HESS J1745-290) variability

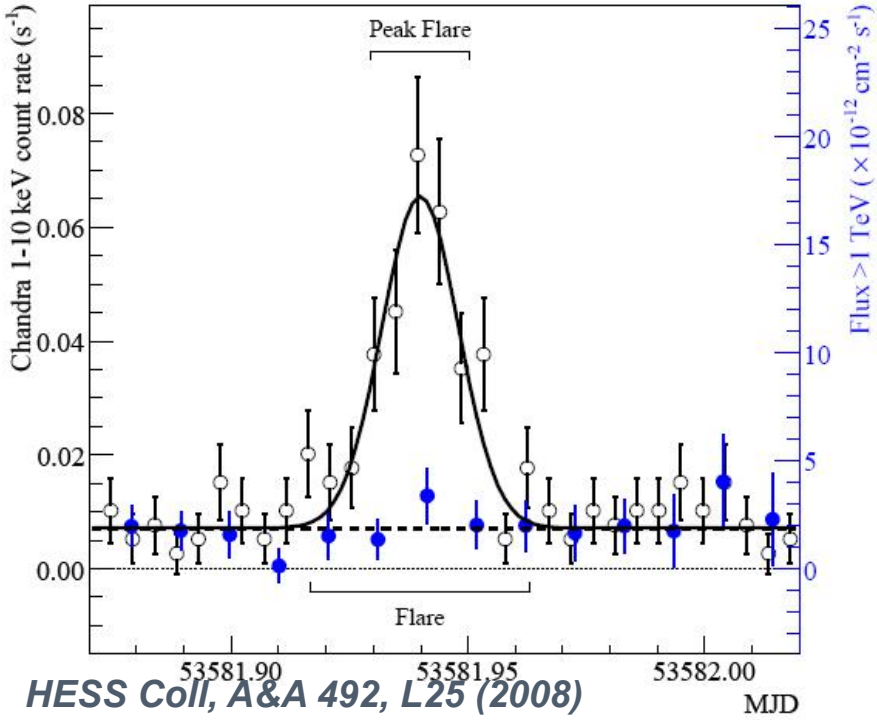
- **No signs variability in VHE lightcurve observed based on 93 hours of data**

- **Simultaneous HESS and Chandra observations in 2005**
- **X-ray flare detected**
  - **1-10 keV**
  - **1600s duration**
  - **9x quiescent level**
- **<u>No increase of gamma flux >1 TeV (factor 2 increase excluded at 99%CL)</u>**

=> disfavours scenarios where keV and TeV emission are associated with the same parent population



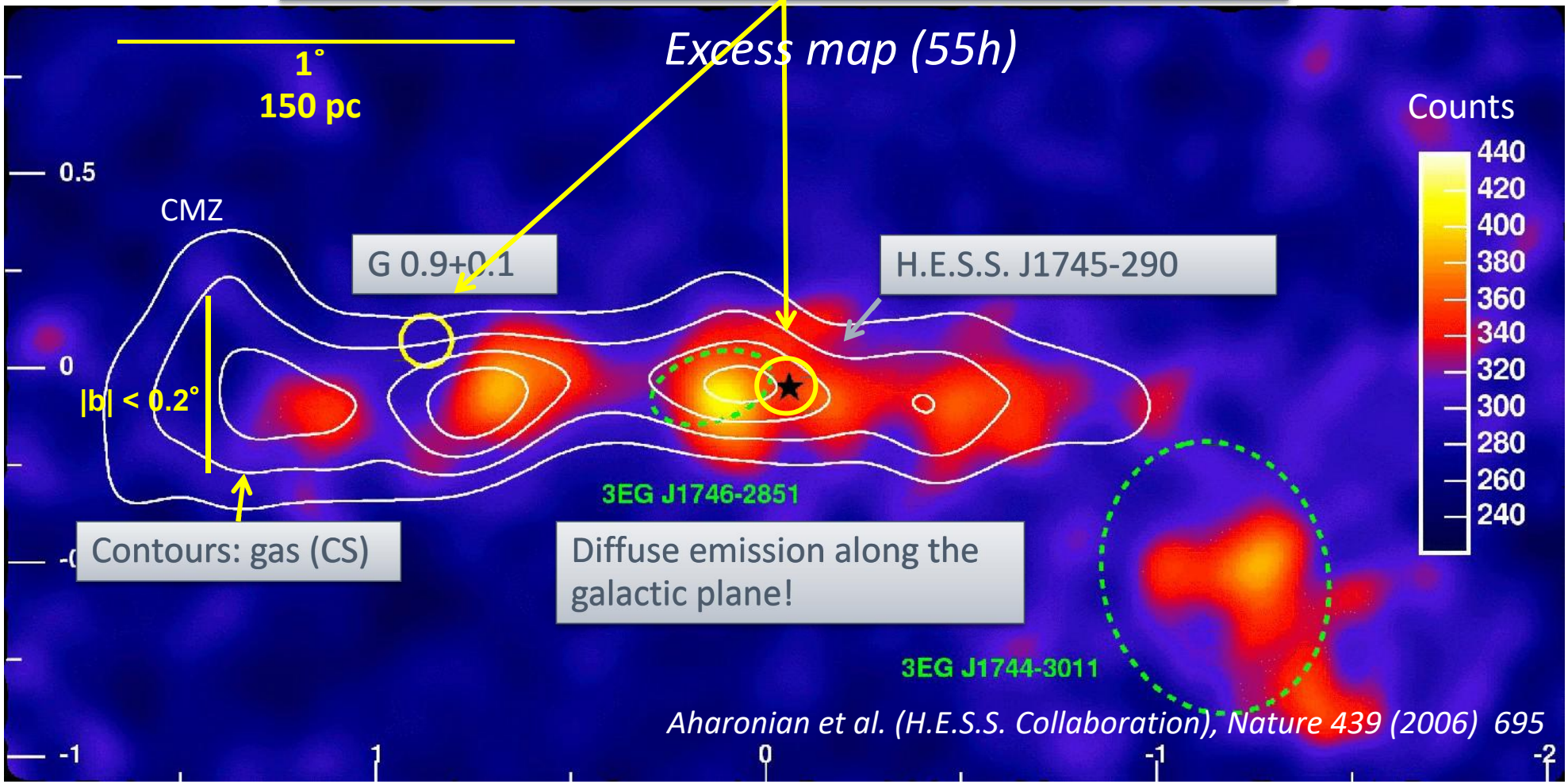




HESS Coll, A&A 492, L25 (2008)

The Galactic Center diffuse emission with H.E.S.S.: 2003-2005

- Search for much fainter emission
- Subtraction of the two bright sources
- Correlation of emission with molecular clouds of the Central Molecular Zone (CMZ) => hadronic origin of emission



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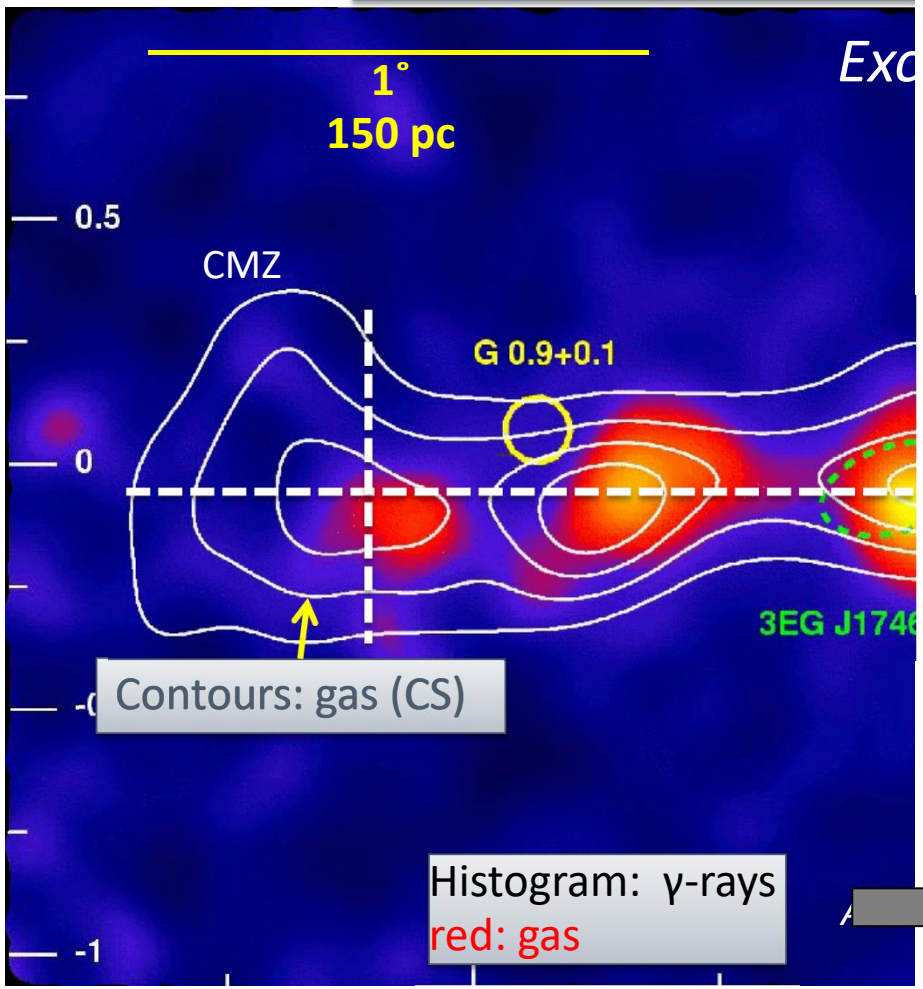
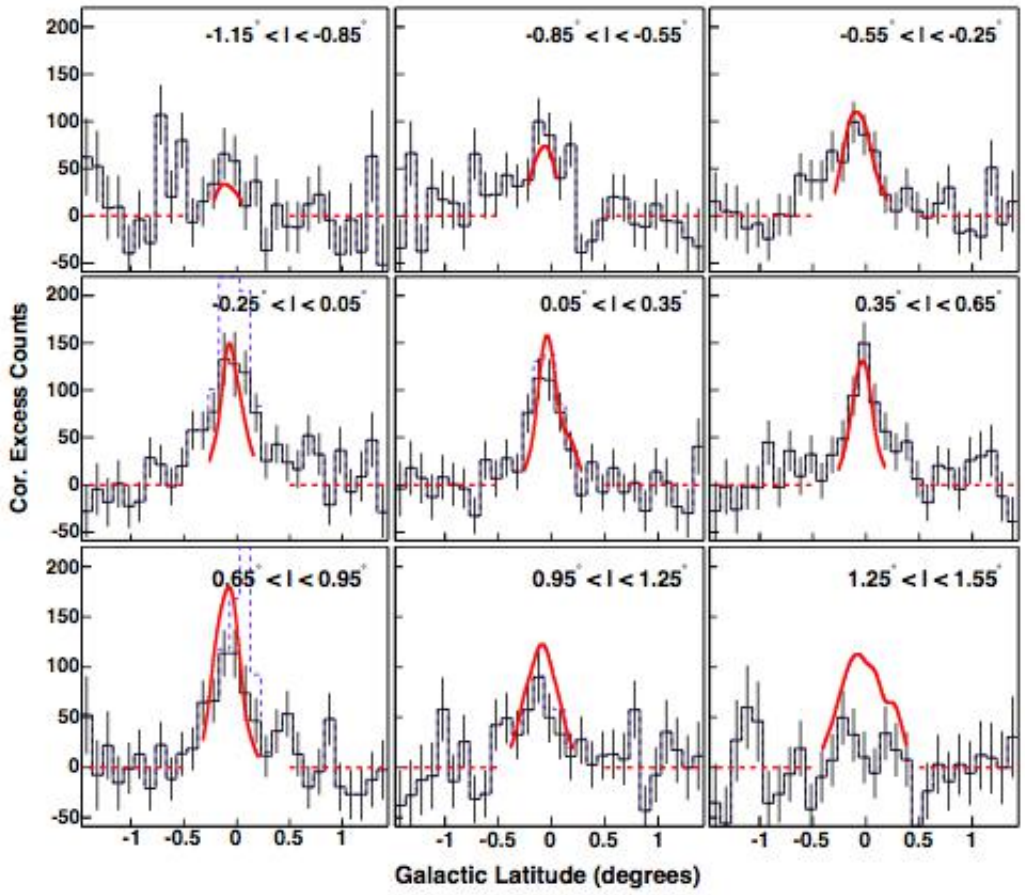
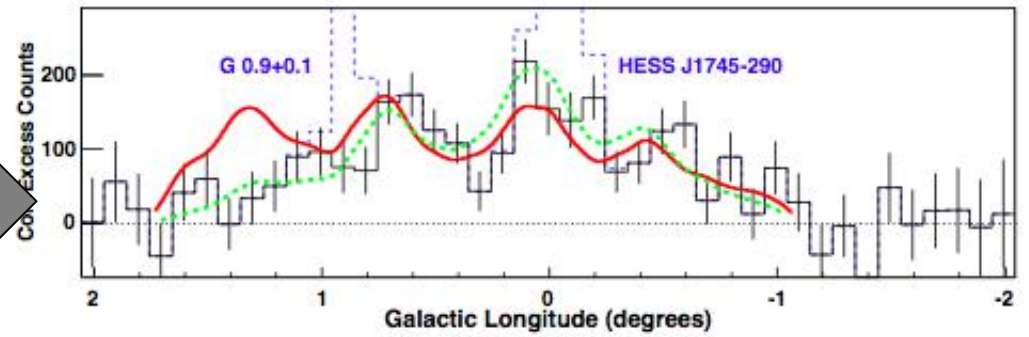


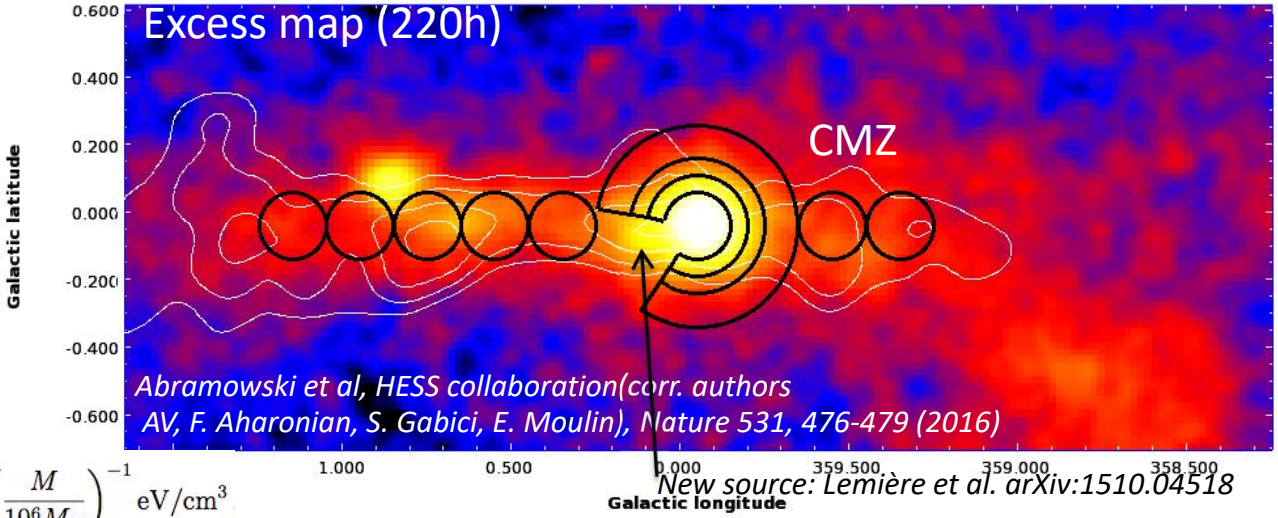




The Galactic Center diffuse emission with H.E.S.S.: 2003-2012 (cosmic-ray energy density distribution)

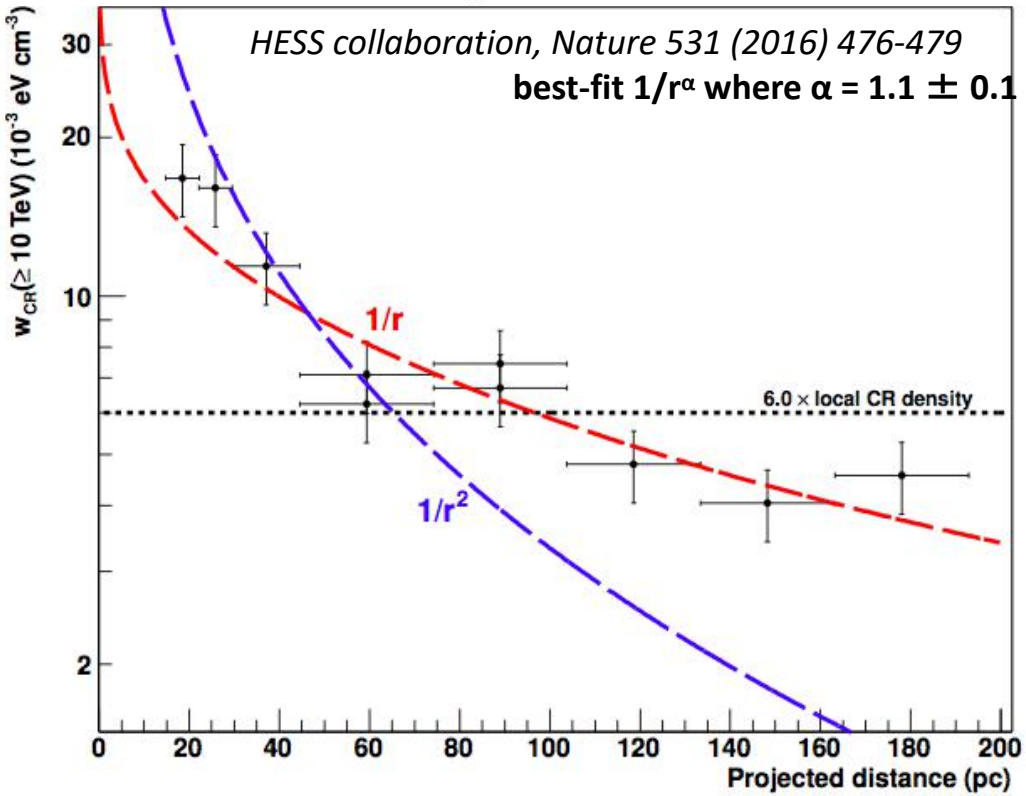
- Correlation with molecular clouds
  => pp interaction target mass (M)
- Gamma-ray luminosity (L) in several regions
- => CR energy density $\propto$ L/M

$$w_{\rm CR}(\geq 10E_\gamma) = \frac{W_p(\geq 10E_\gamma)}{V} \sim 1.8\times10^{-2}\left(\frac{\eta_N}{1.5}\right)^{-1}\left(\frac{L_\gamma(\geq E_\gamma)}{10^{34}{\rm erg/s}}\right)\left(\frac{M}{10^6 M_\odot}\right)^{-1} {\rm eV/cm^3}$$



Abramowski et al, HESS collaboration(corr. authors AV, F. Aharonian, S. Gabici, E. Moulin), Nature 531, 476-479 (2016)

New source: Lemière et al. arXiv:1510.04518



Cosmic-ray energy density distribution

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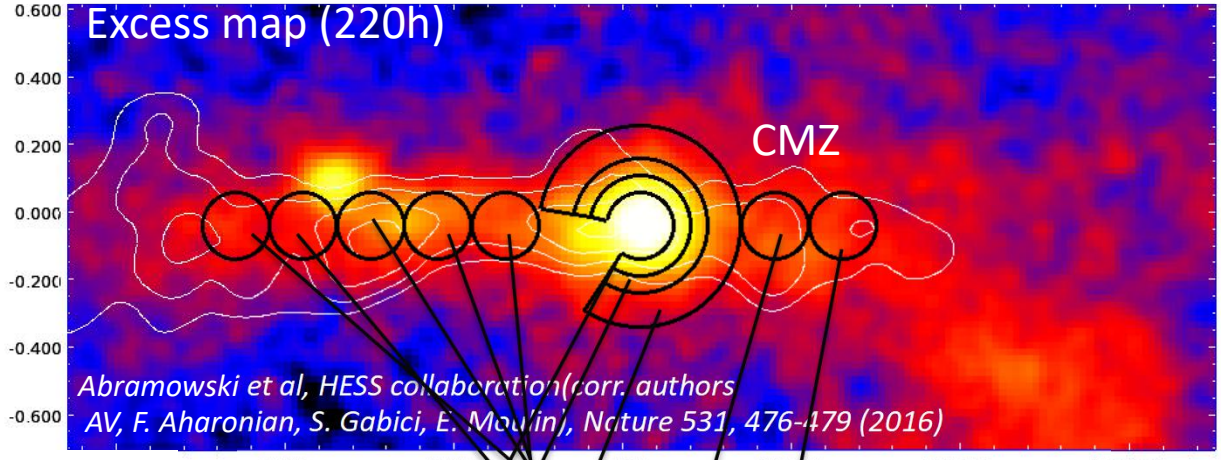

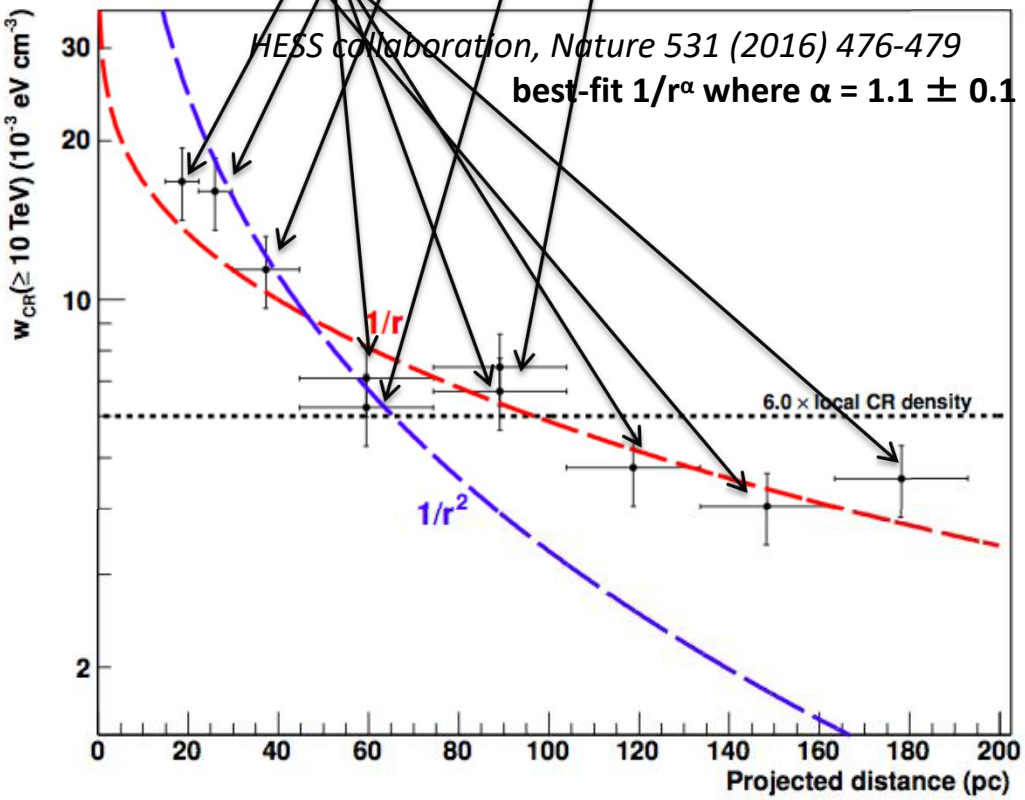

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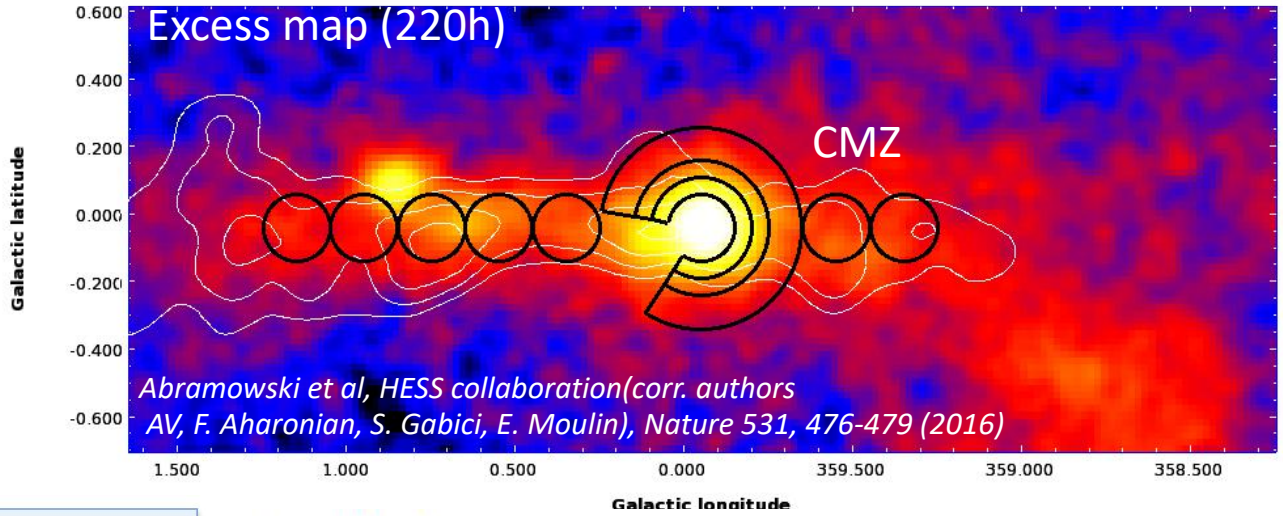
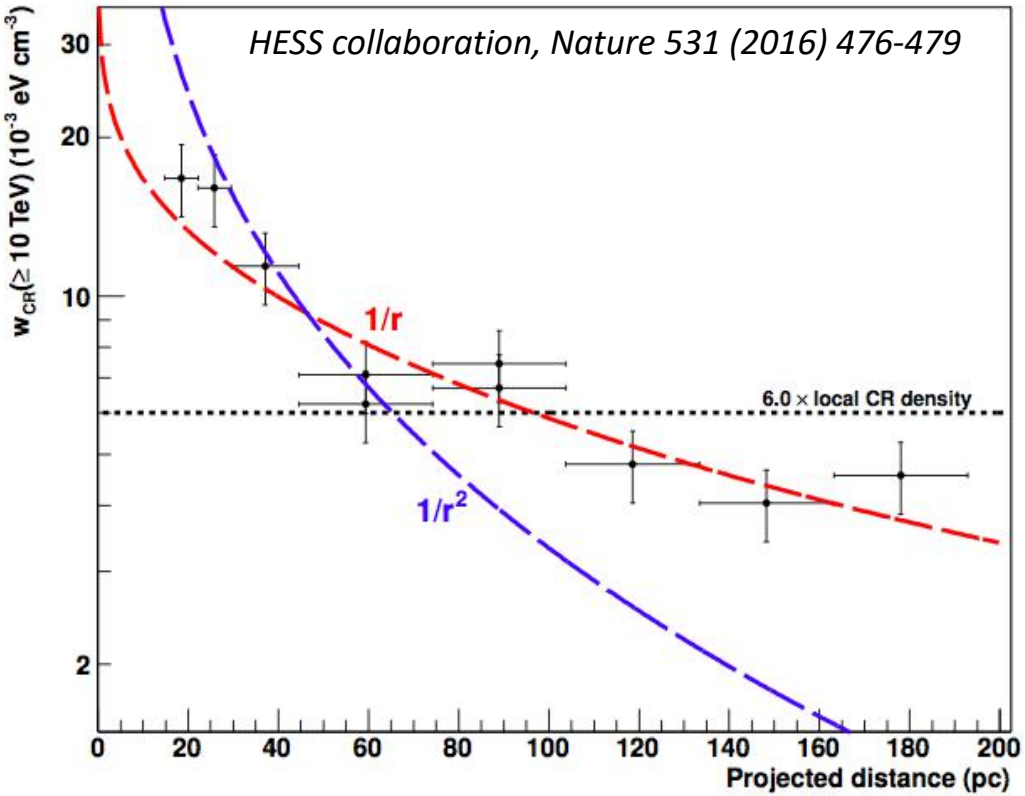


CR density radial distributions meanings:

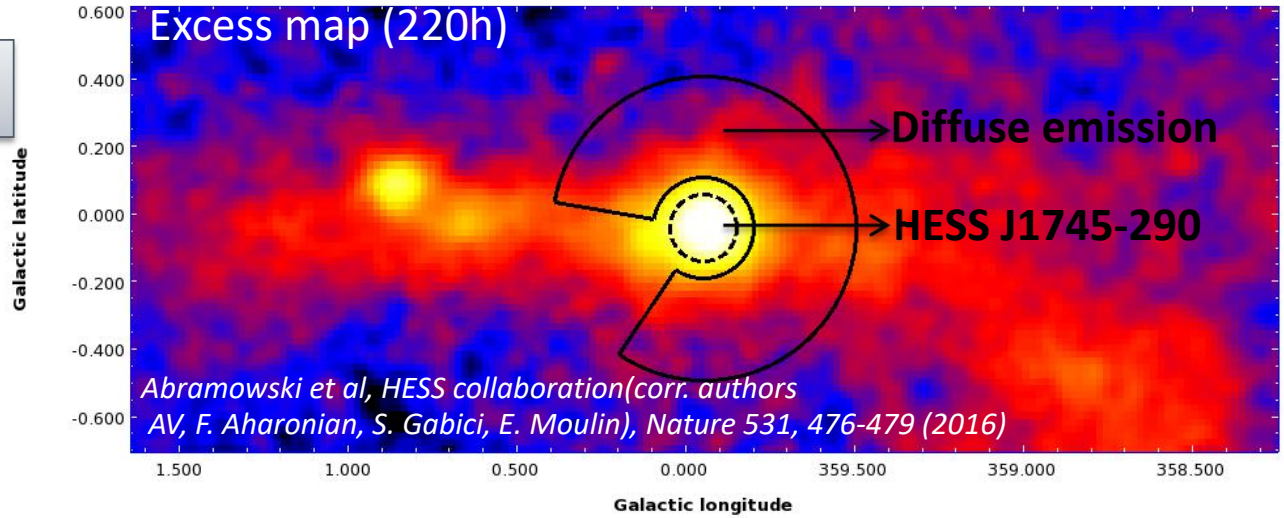
- **Homogeneous/Constant**
  - Impulsive injection of CRs and diffusive propagation
- **$1/r^2$**
  - Wind-driven or ballistic propagation
- **1/r**
  - continuous injection and diffusive propagation



Central accelerator located within 10 pc and injecting CRs continuously over more than 1000 years

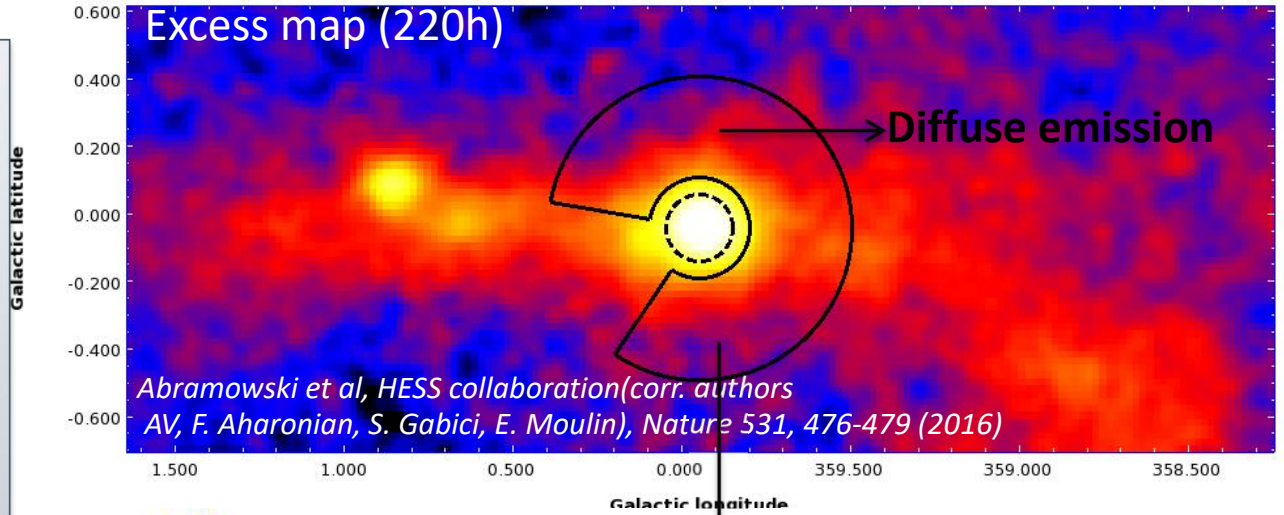
Diffuse gamma-ray emission and injection spectra

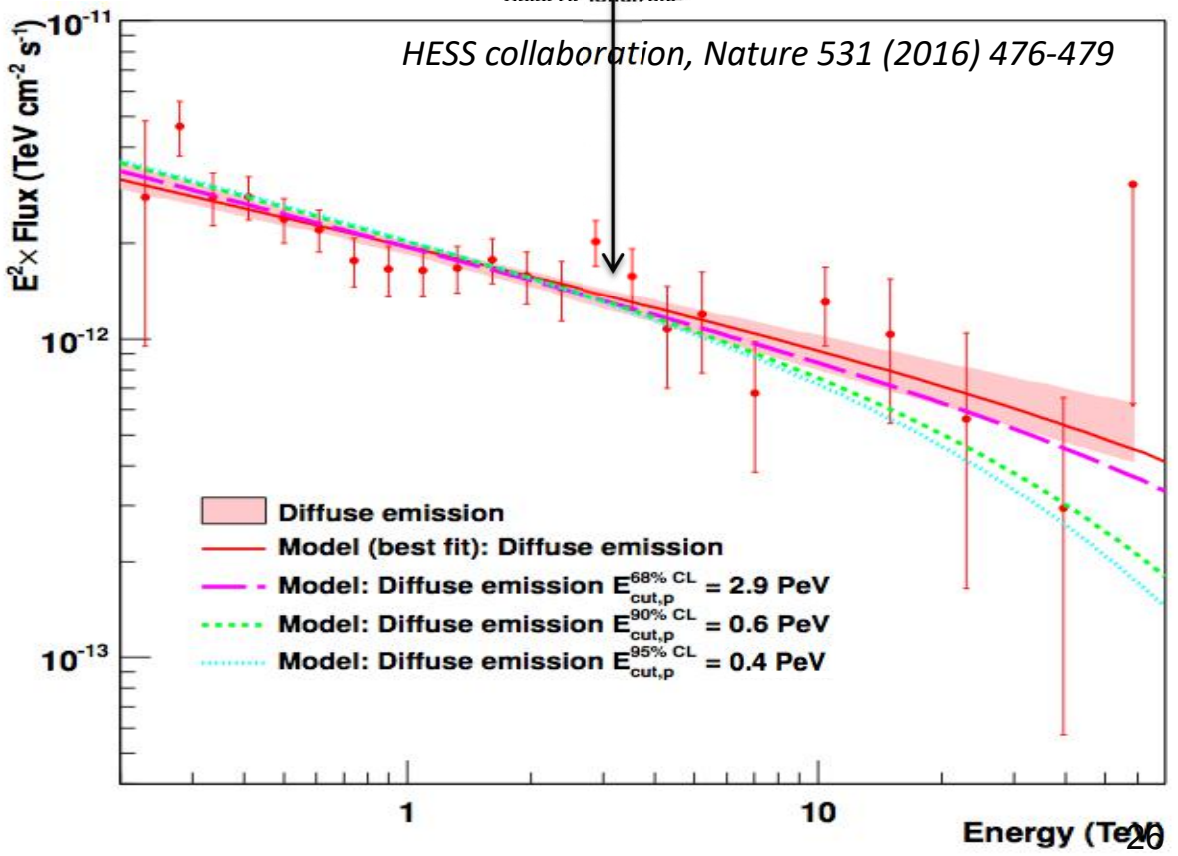
- Spectrum diffuse emission extracted from large ring $[r_{in}, r_{out}] = [0.15^{o}, 0.45^{o}]$



Diffuse gamma-ray emission and injection spectra

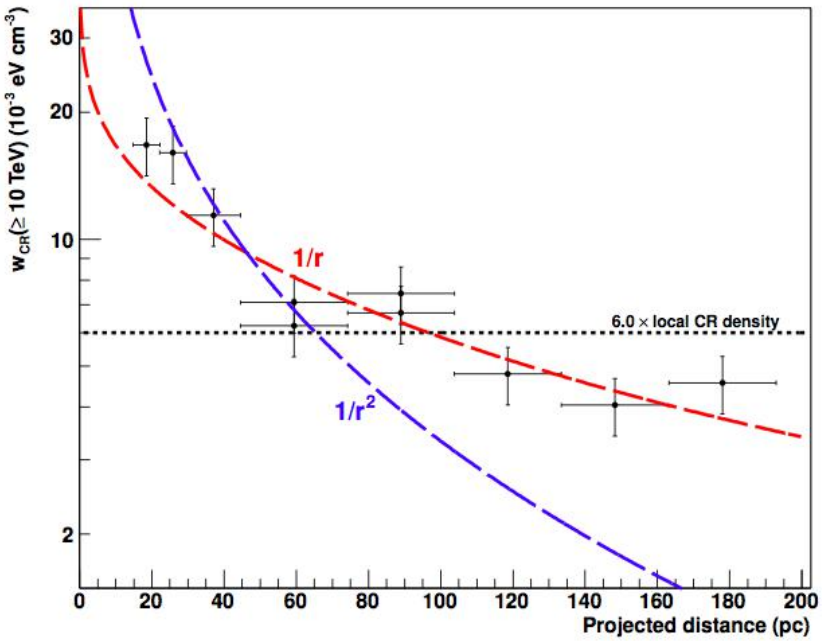
- Spectrum diffuse emission extracted from large ring $[r_{in}, r_{out}] = [0.15^o, 0.45^o]$
- Spectrum of diffuse emission: power-law with index 2.3 extending up to 50 TeV without energy cut-off
- Parent proton injection spectrum should extend to PeV energies
  - quasi-continuous injection lasting over ~10^4 years
  - total CR power injected at the GC ~10^{38} erg/s



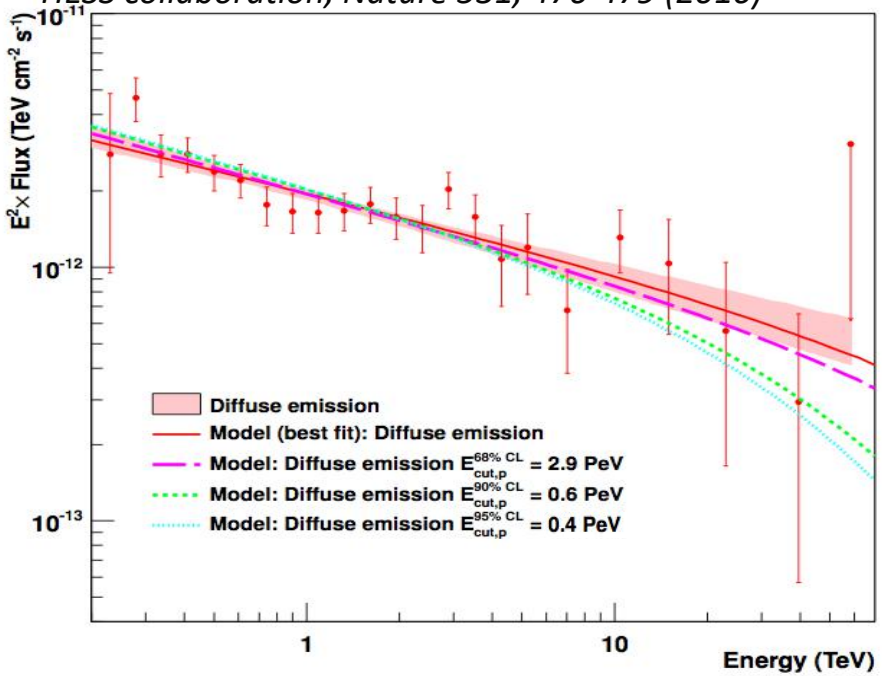


First robust detection of a cosmic Galactic PeVatron!

Galactic Centre as a powerful Pevatron



HESS collaboration, Nature 531, 476-479 (2016)



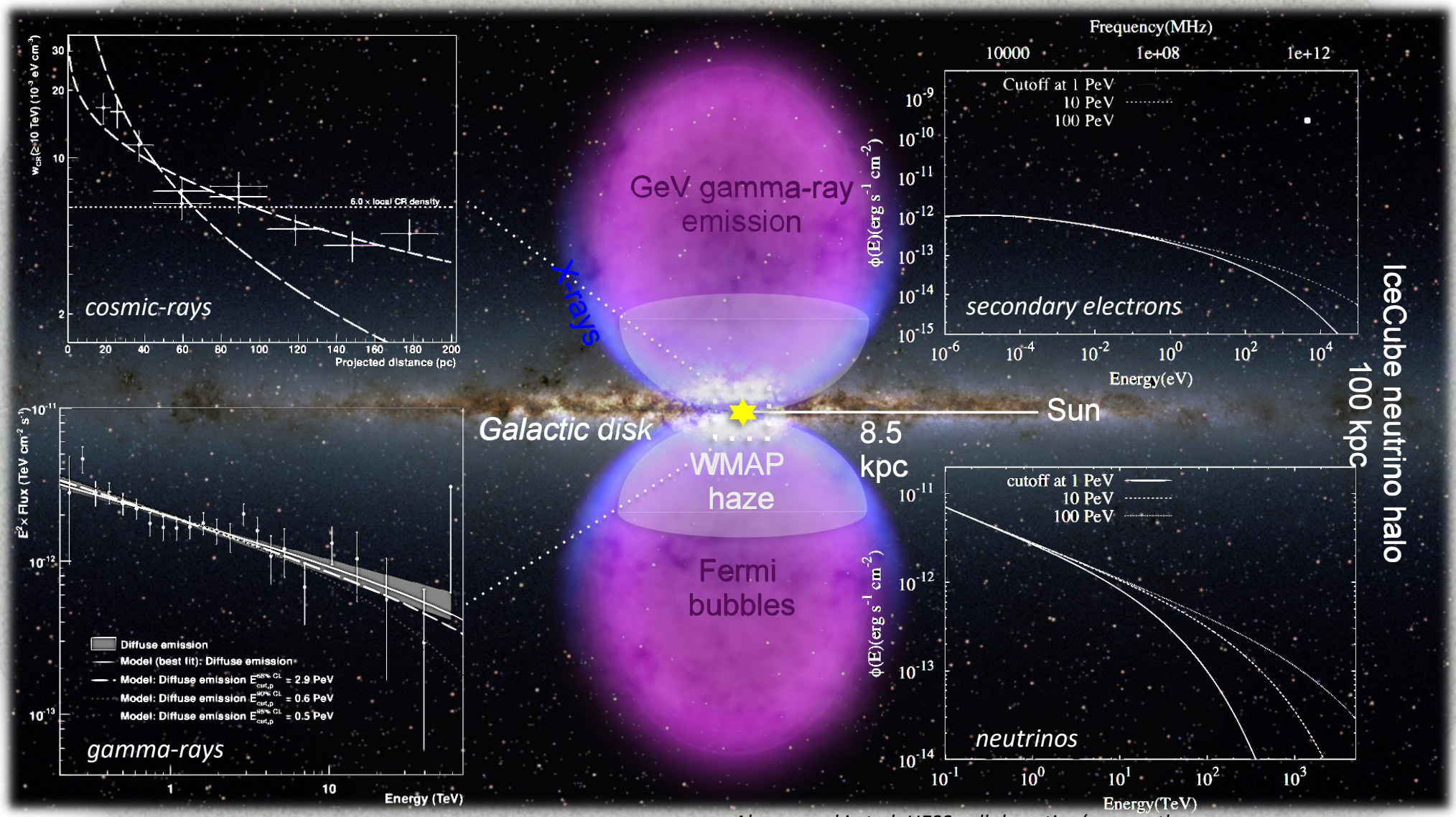
- Given the location (< 10 pc), the maximum acceleration energy (~PeV), the continuous power and age of the accelerator only the **SMBH Sgr A*** is a viable couterpart

- A significant fraction of accretion in Sgr A* is released through acceleration of particles to ultrahigh energies

- SgrA* has been more active in the past (Ponti et al. 2010/12, Terrier et al. 2010) => **if injection power ≥ 10^{39} erg/s, GC PeVatron can explain the fluxes of Galactic CRs above 100 TeV to a few PeV (region of the "knee")**

- Possible origin of two large scale structures : **Fermi Bubbles** observed by Fermi-LAT (Su et al. 2010, Crocker & Aharonian 2010) and isotropic flux of the **extraterrestrial neutrinos** discovered recently by IceCube (Taylor et al. 2014)

Galactic Centre as a powerful Pevatron



Abramowski et al, HESS collaboration(corr. authors AV, F. Aharonian, S. Gabici, E. Moulin), Nature 531, 476-479 (2016)

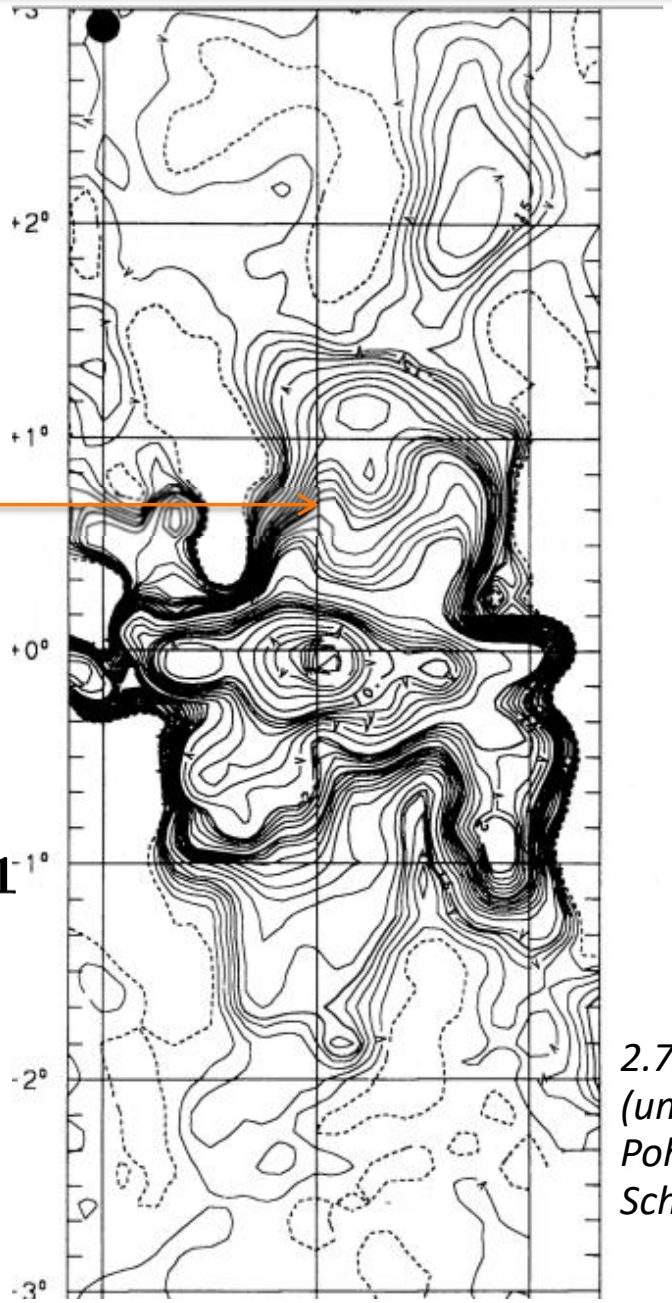
Evidence of Centrally Powered Escape?

$$v_{\rm wind} \approx 500 \text{ km s}^{-1}$$

$$\dot{M} \approx 0.1 \ M_{\odot} \text{ yr}^{-1}$$

$$\dot{E}_{\rm wind} \approx 3 \times 10^{40} \text{ erg s}^{-1}$$

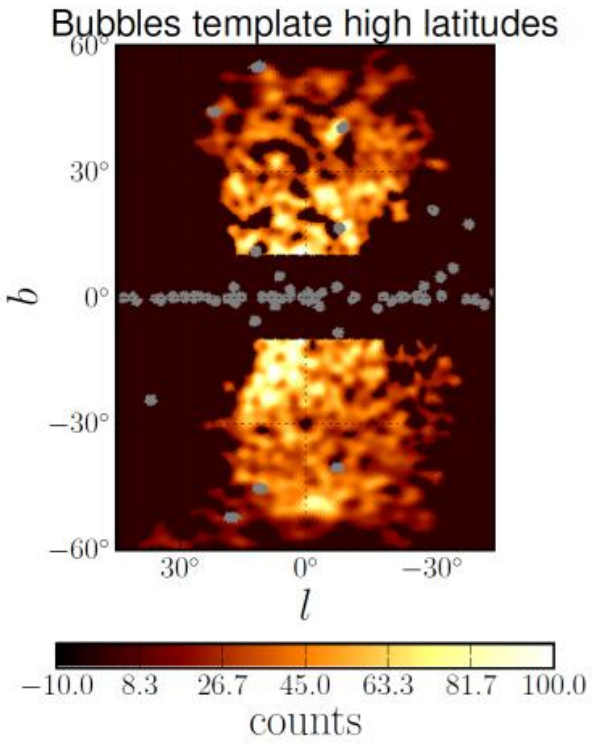
arxiV:1412.7510

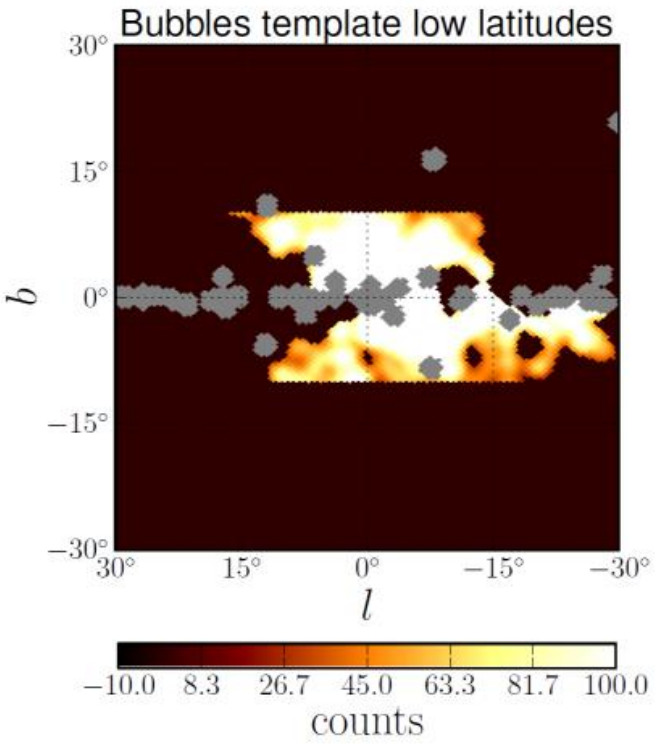


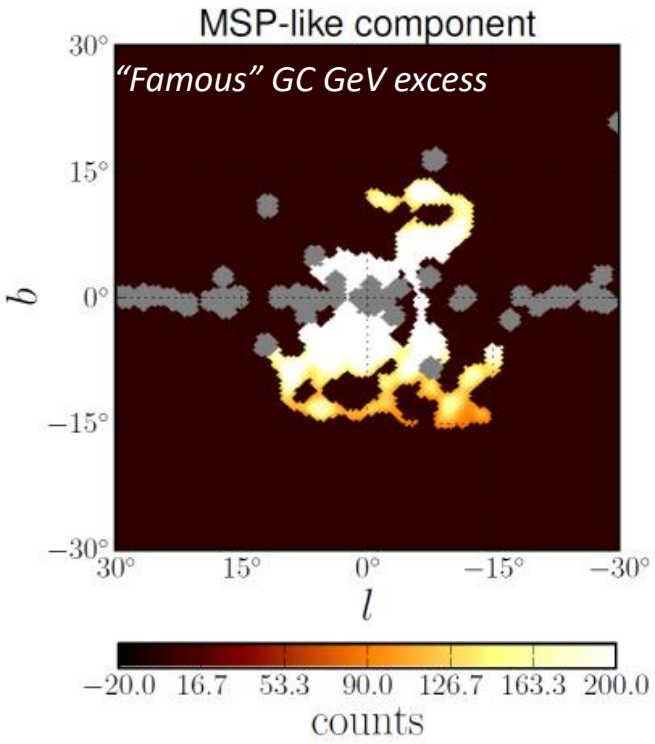
2.7 GHz radio data (unsharp mask, 9.4`) Pohl, Reich & Schlickeiser 1992

Fermi Bubble templates

- The Fermi Bubbles at latitudes b> 10^{o} seems to have the same spectrum and intensity all over
- Recent analysis of the Inner Galaxy by Fermi-LAT showed that the Fermi Bubble emission for b<10^{o} increases in intensity and it has a harder spectral index (-1.9-2.0) without sign of cut-off up to at least 1 TeV







arXiv:1704.03910

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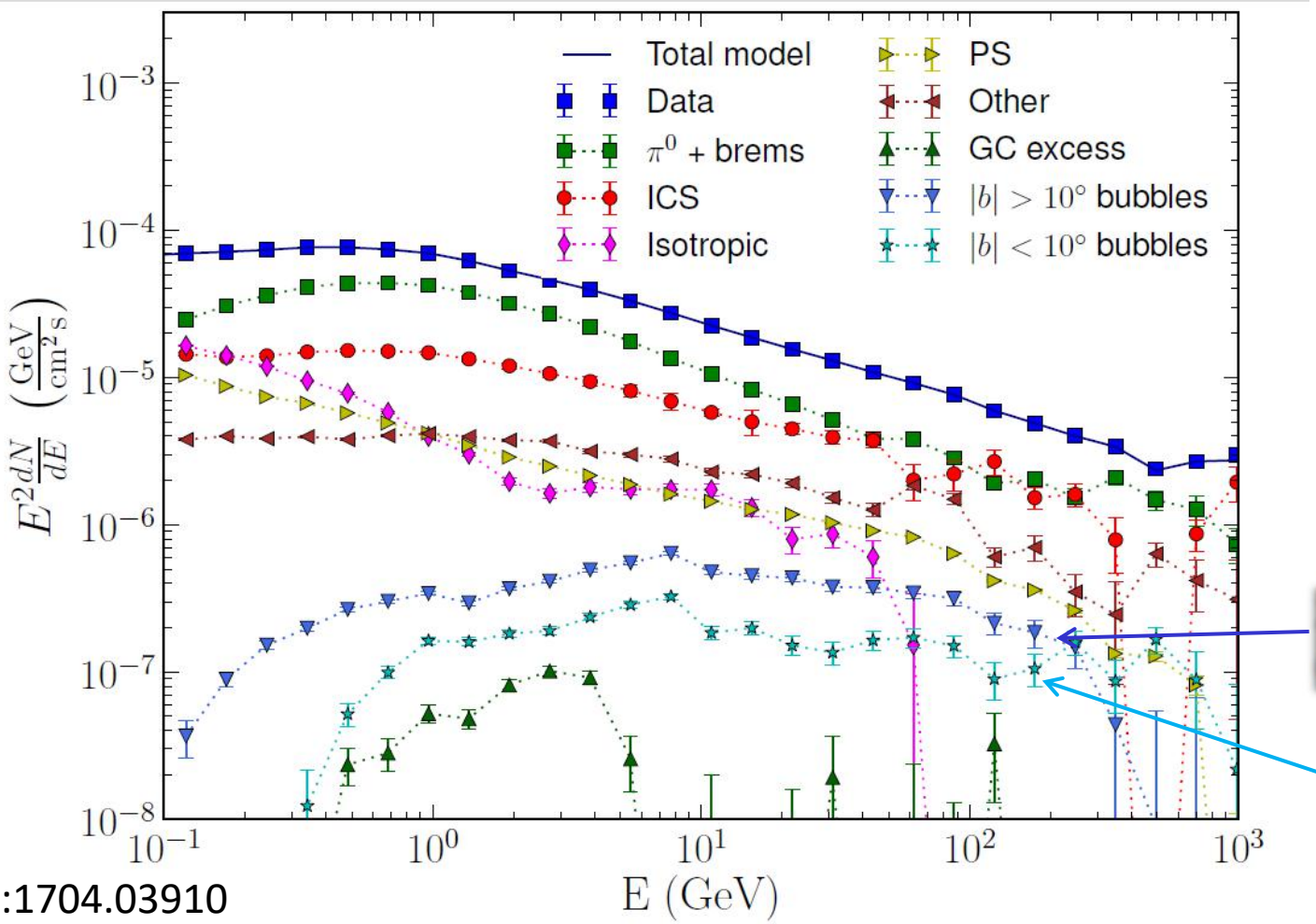


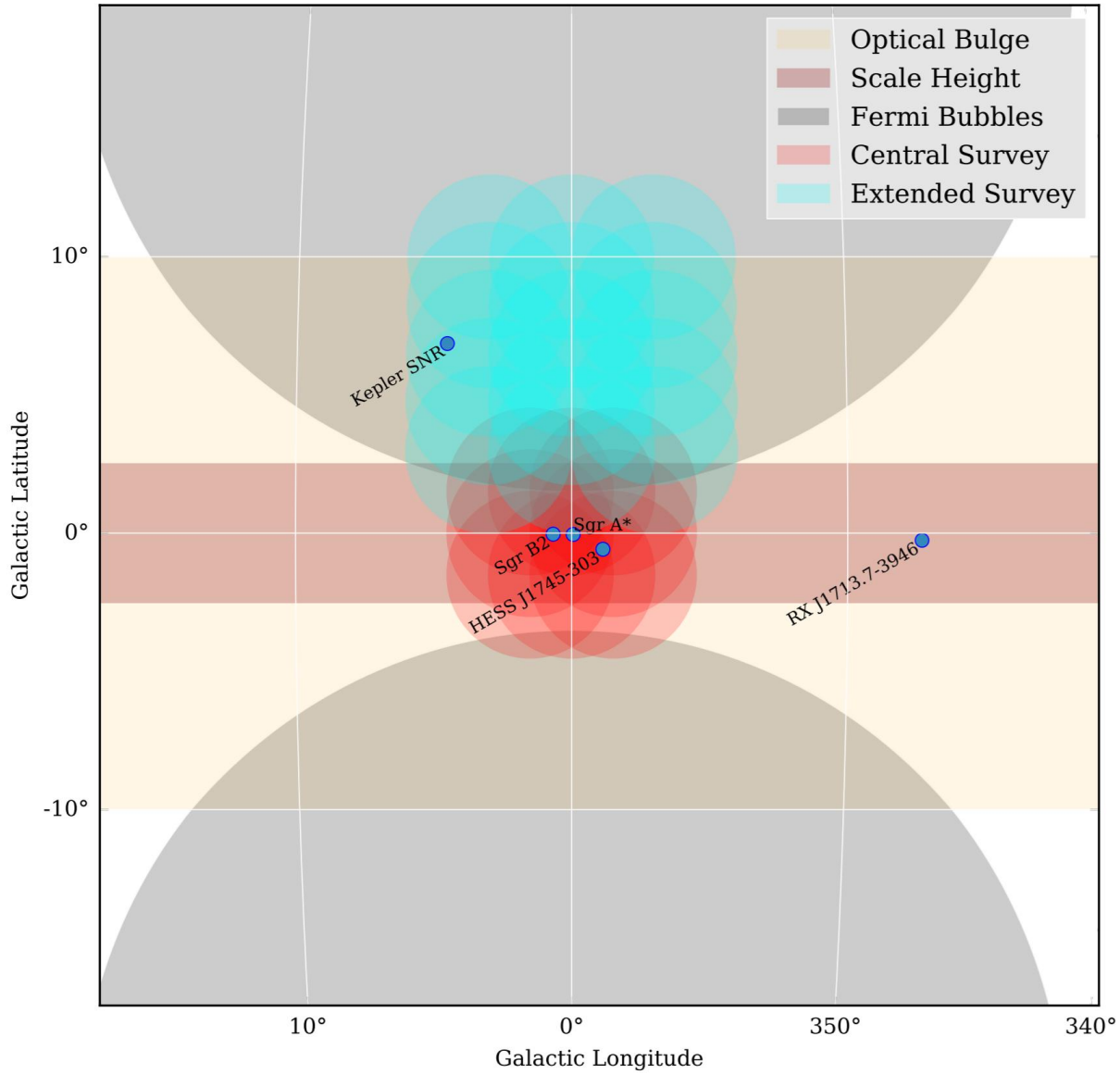
2.4 index power-law with cut-off at 100-300 GeV

1.9-2.0 index power-law with no cut-off

arXiv:1704.03910

Future with CTA

Galactic Centre Key Science Project [825 h]



➢ **Large field of view** => more detailed view of the Diffuse VHE emission (new sources, outflows, etc)

➢Improved PSF (r68~0.02˚-0.03 ˚), pointing accuracy (3”) and sensitivity => **resolve GC source** (e.g.: 0.5‘ (0.01 ˚); size of circumnuclear disk; distinguish Sgr A* and PWN

➢**Search for a possible time dependent component =>** Sgr A* MWL observations with IR/ X-ray instruments and improved sensitivity to flux variation for flares (typically 1h)

➢**Search for long term flux evolution** => Expected if energetic protons accelerated during past periods of increased activity of Sgr A*

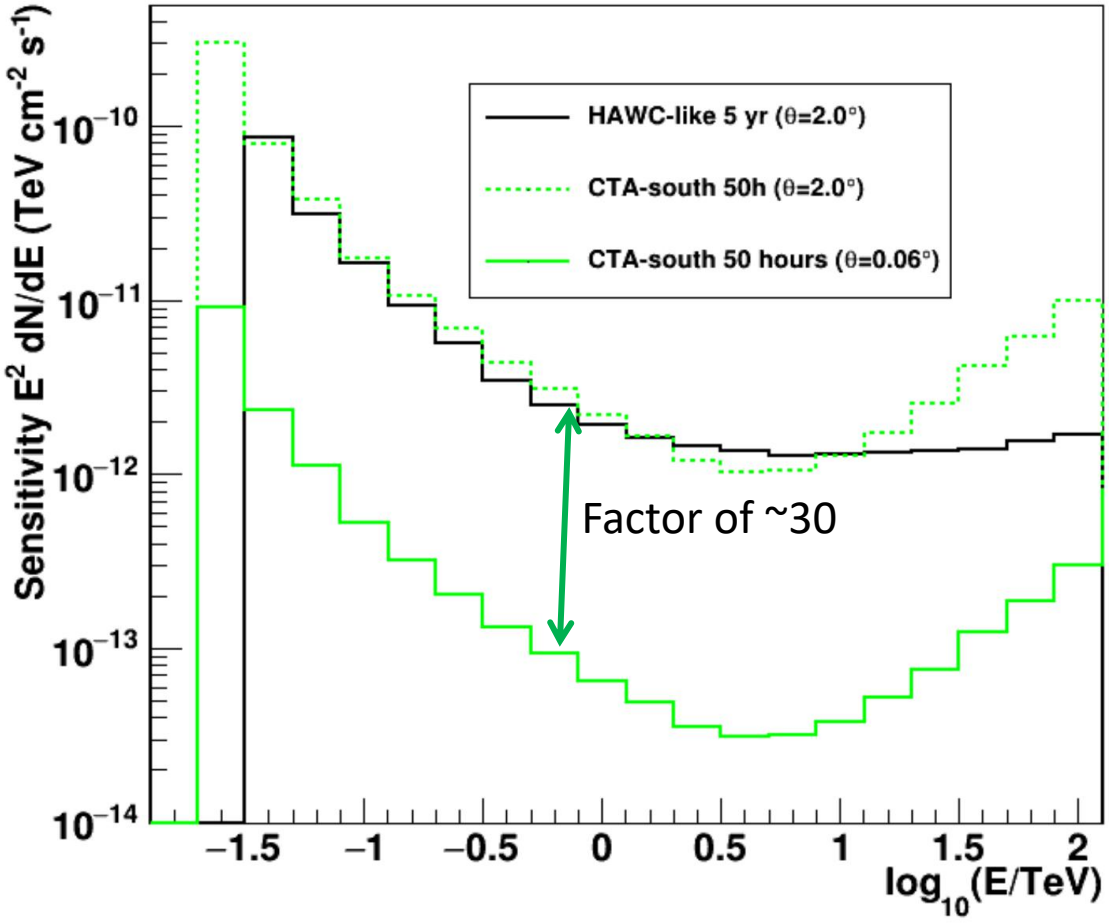
A Southern Wide-field gamma-ray observatory

Can a Southern wide-field gamma-ray observatory be relevant for the study of large-scale emission in the GC and Inner Galaxy regions?

A Southern Wide-field gamma-ray observatory

Can a Southern wide-field gamma-ray observatory be relevant for the study of large-scale emission in the GC and Inner Galaxy regions?

- Sensitivity scales with θ(=radius of region)
- For isotropic sources flux increases with θ^2 so significance should increase with $S/\sqrt{B}$ propto θ
- The superior sensitivity of CTA to steady sources comes mainly from its very small angular resolution
- CTA will still suffer to measure residual hadronic background for sources larger than its field-of-view (to date there is no available method)



For sources larger than ~2.0° CTA-south 50h sensitivity becomes comparable to a 5yr HAWC-like detector below 1 TeV!

Summary and conclusions

- Galactic Center is the richest environment in the Galaxy to study high energy phenomena: supermassive blackhole, cosmic-rays, dark matter....

- Gamma-ray spectrum strongly suggests that SMBH Sgr A* is a hadronic cosmic-ray accelerator continuously injecting particle for the past > 10^3 to PeV energies -> **First robust detection of cosmic Galactic PeVatron**

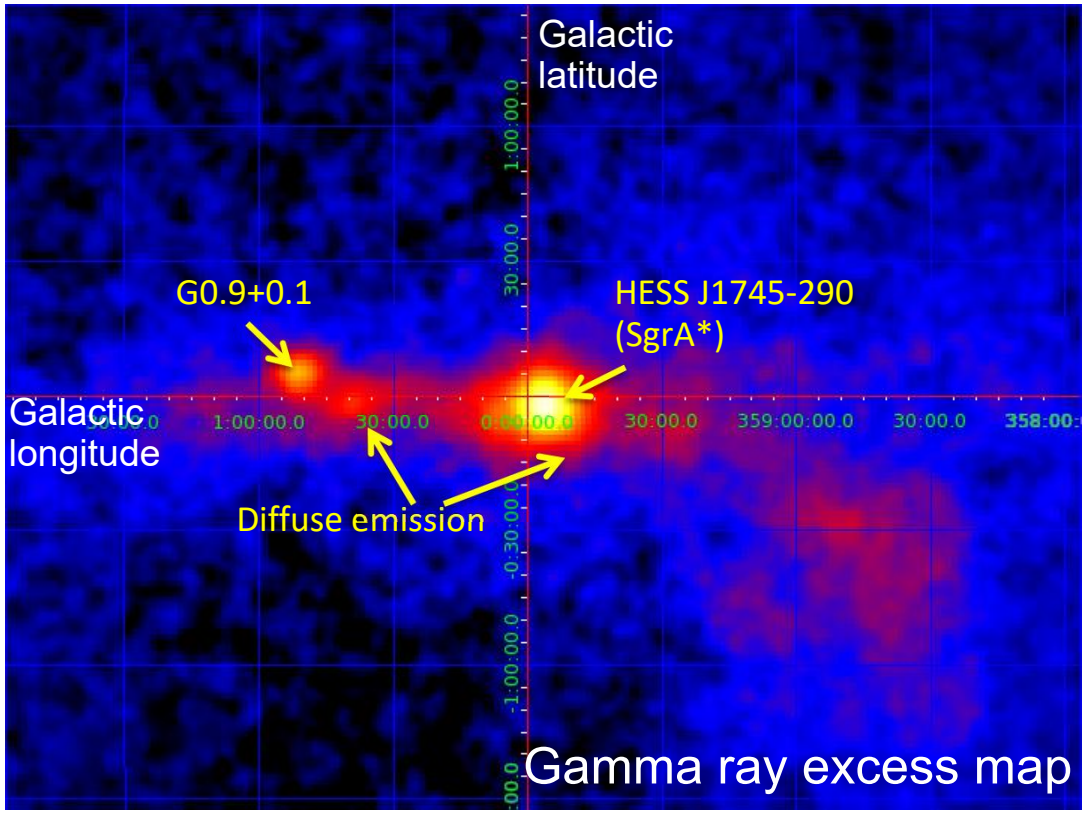
- Total CR power injected at the GC ~10^{38} erg/s. SgrA* has been more active in the past => **GC PeVatron could explain the fluxes of galactic CRs above 100 TeV to a few PeV (region of the "knee") , Fermi Bubbles and extraterrestrial neutrinos**

- Recent Fermi Bubbles measurements suggest low latitude component with hard spectrum -> possible link to a GC outflow

- A Southern wide-field gamma-ray observatory could be highly competitive to CTA for large-scale emissions -> it can play a very important role to understand GC energy feedback to Galaxy, past SMBH activity, etc...

H.E.S.S. observations of the Galactic Centre

- 10-year observations with H.E.S.S. 1 provides more than 250 hours towards the GC
- Very bright gamma-ray emission along the Galactic pane



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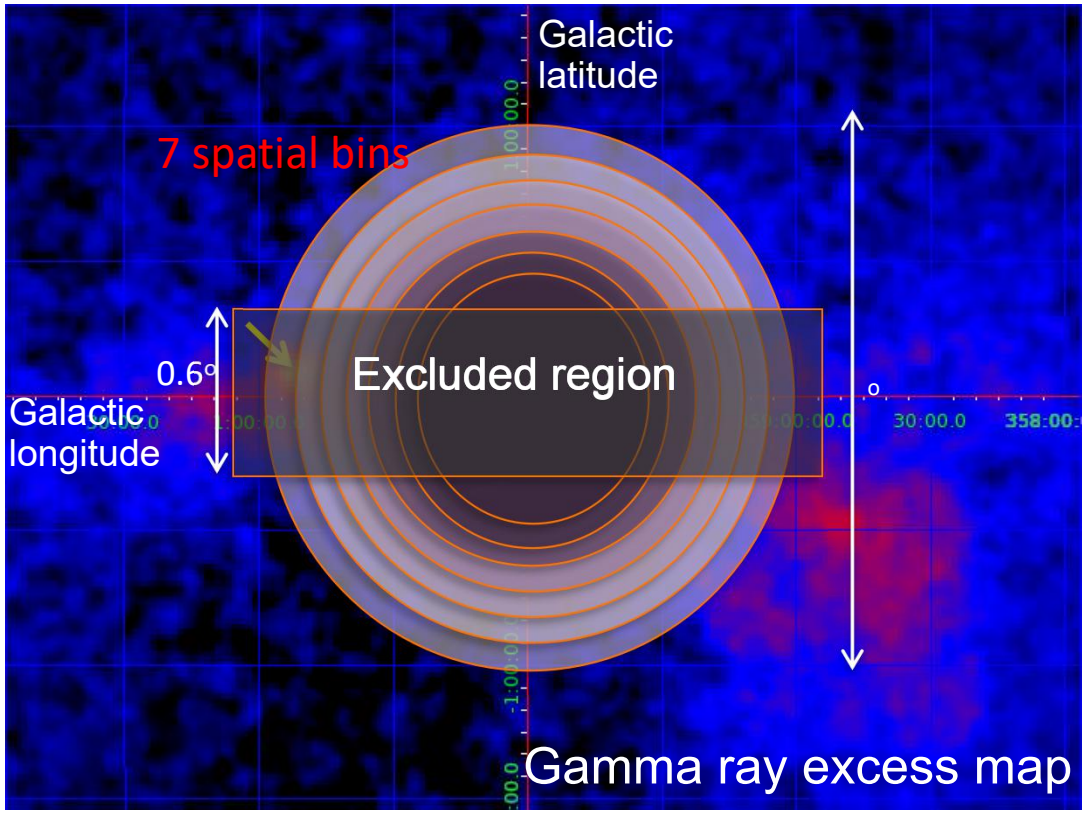
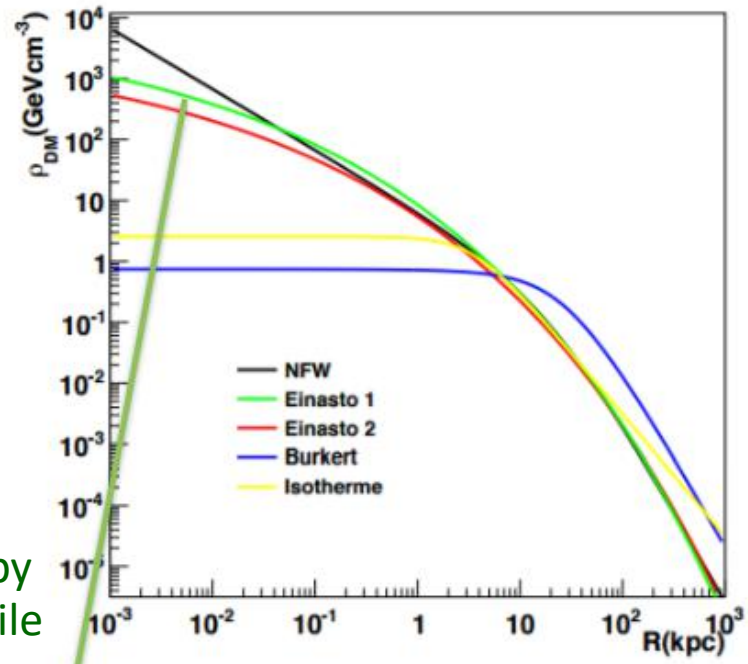


Dark Matter distribution in the GC



Cuspy profile

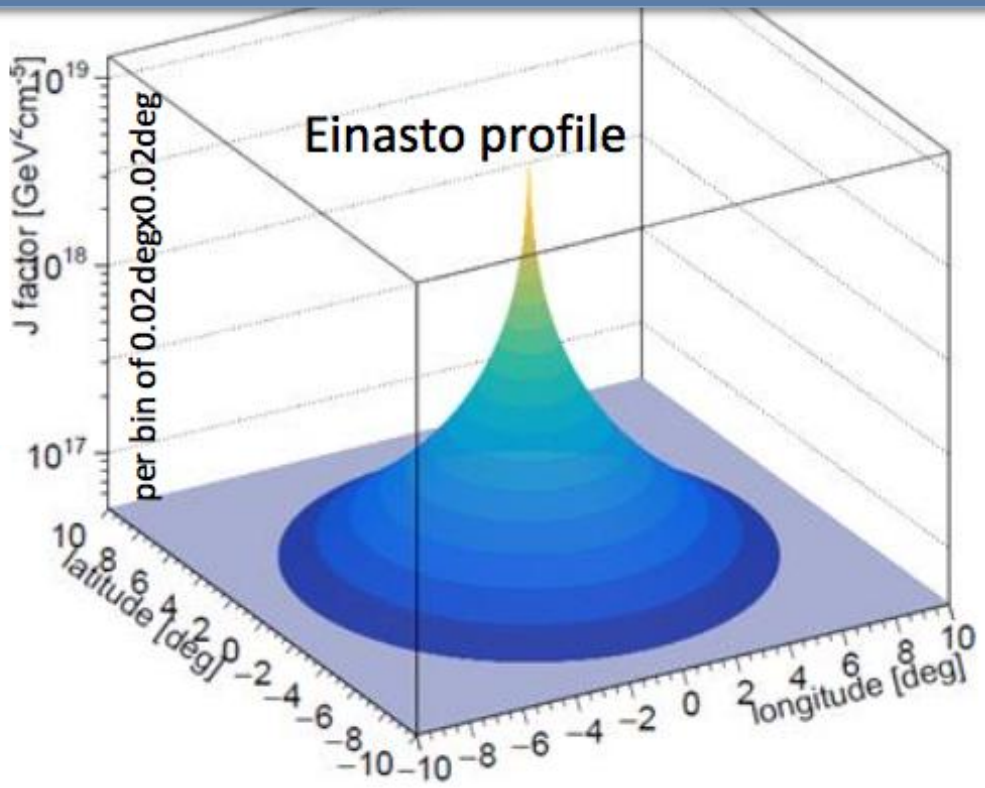
$$\rho_{Ein1}(r) = \rho_s \exp\left[\frac{-2}{\alpha}\left(\left(\frac{r}{r_s}\right)^{\alpha} - 1\right)\right]$$

parametrized with

$\alpha = 0.17$

$r_s = 21\ kpc$

$\rho_s = 0.07\ GeV cm^{-3}$



- We assumed an Einasto profile
- The spatial morphology can be used to discriminate between a DM gamma-ray signal and the residual isotropic hadronc background

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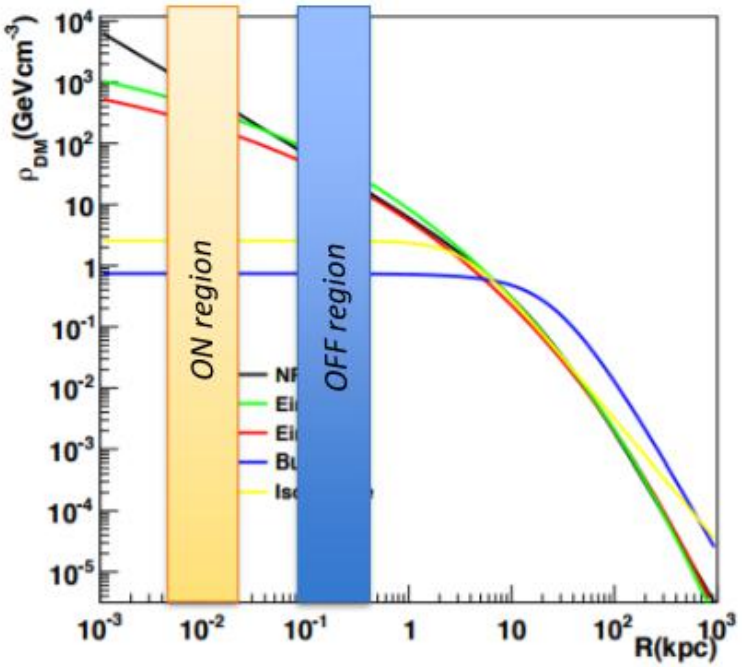

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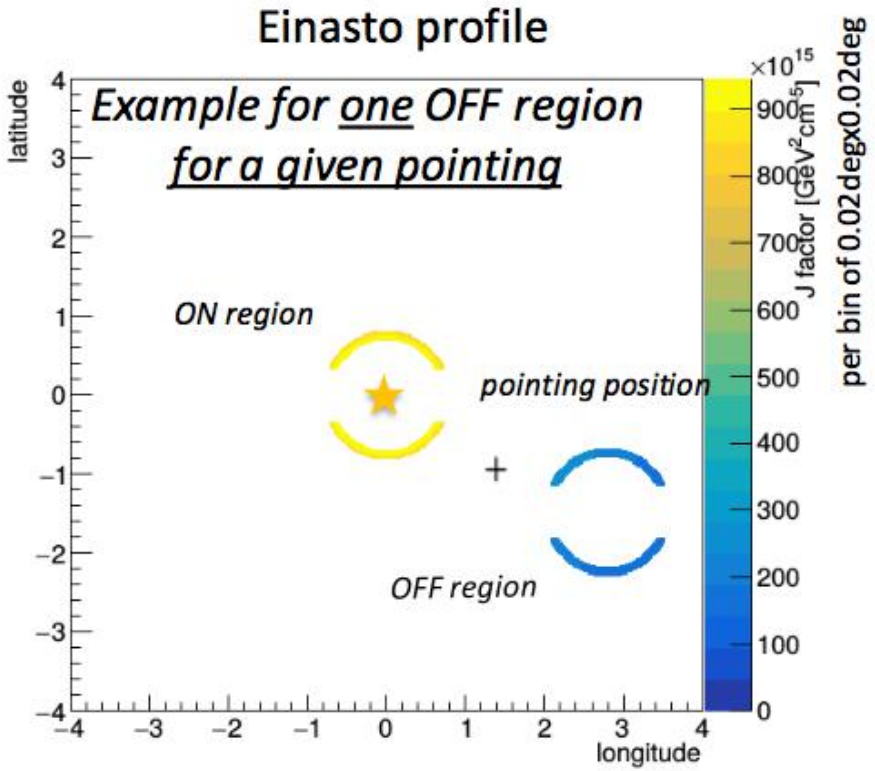

- We assumed an Einasto profile
- The spatial morphology can be used to discriminate between a DM gamma-ray signal and the residual isotropic hadronc background
- Large gradient between ON (signal) and OFF (background region)

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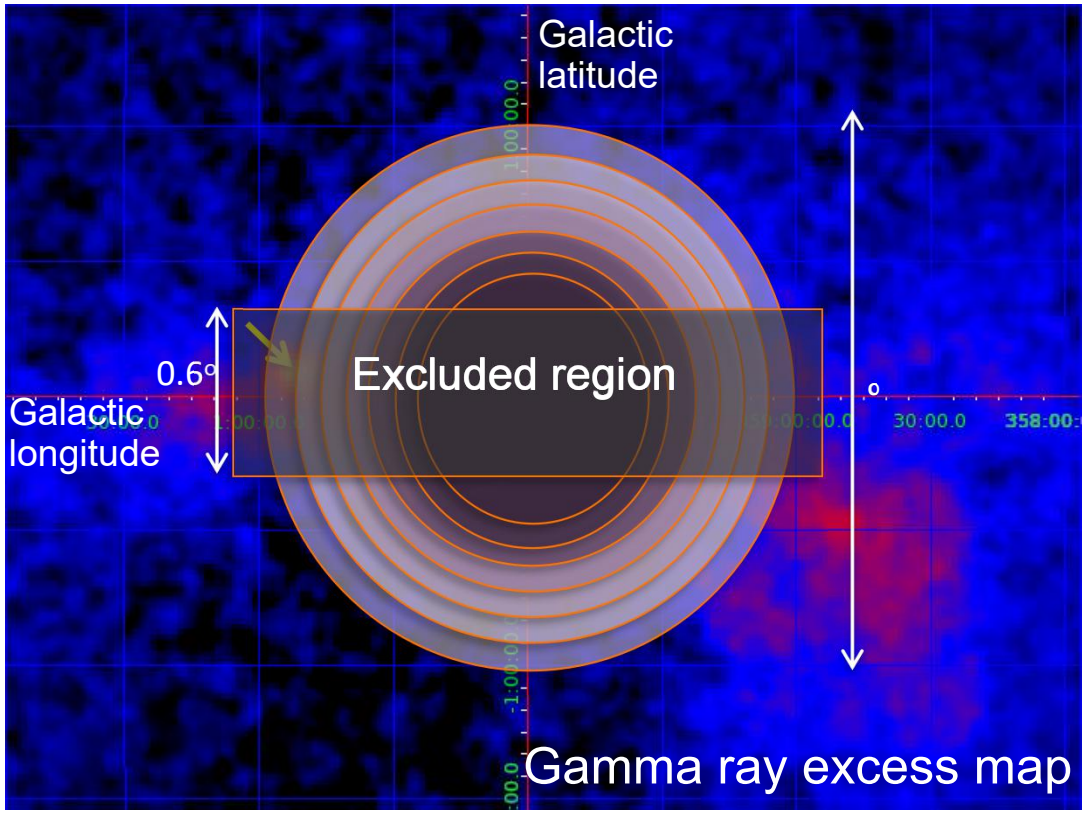
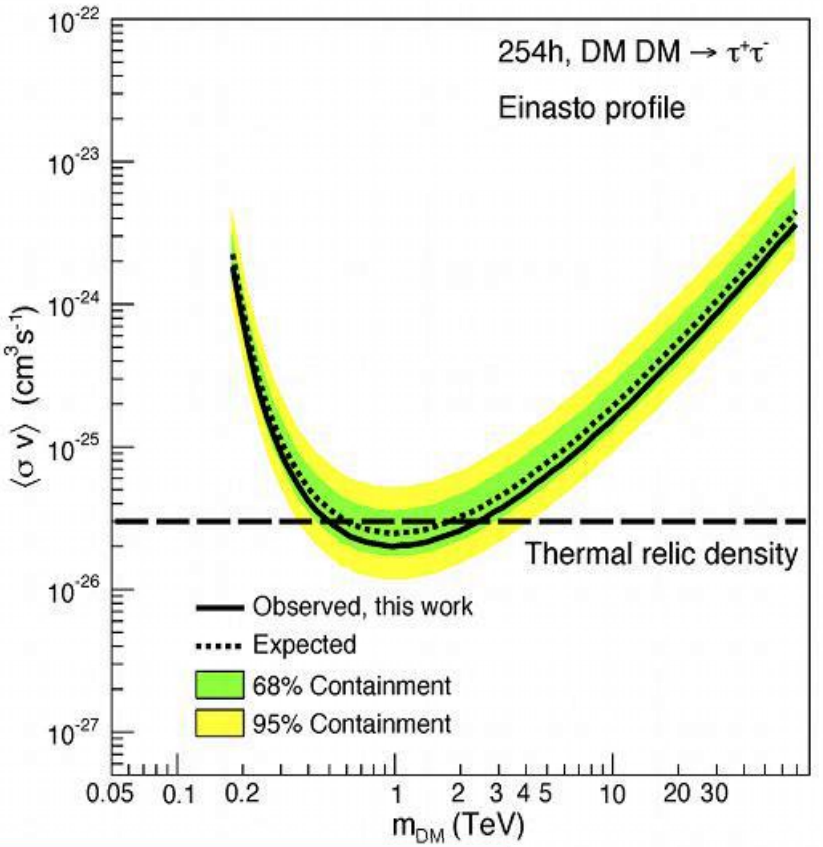




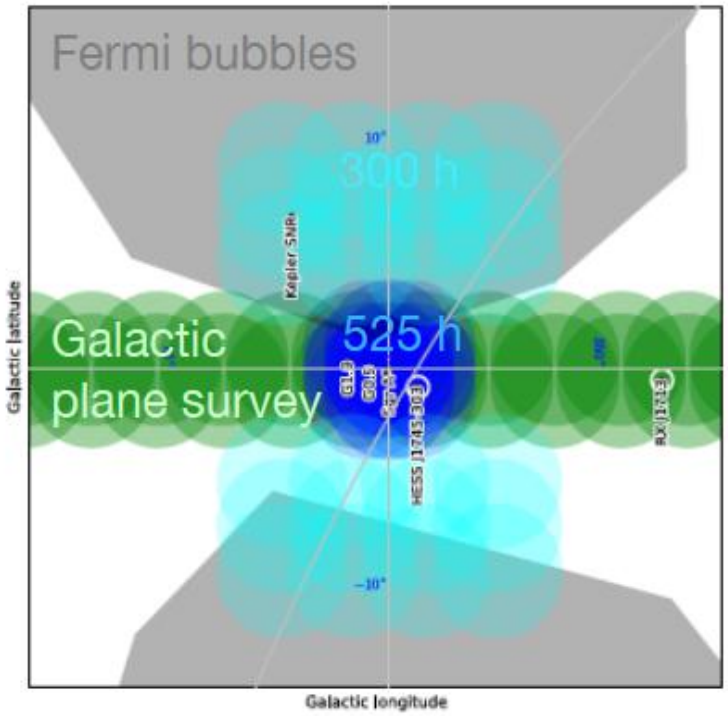
H.E.S.S. Coll., PRL. 117, 111301 (2016)

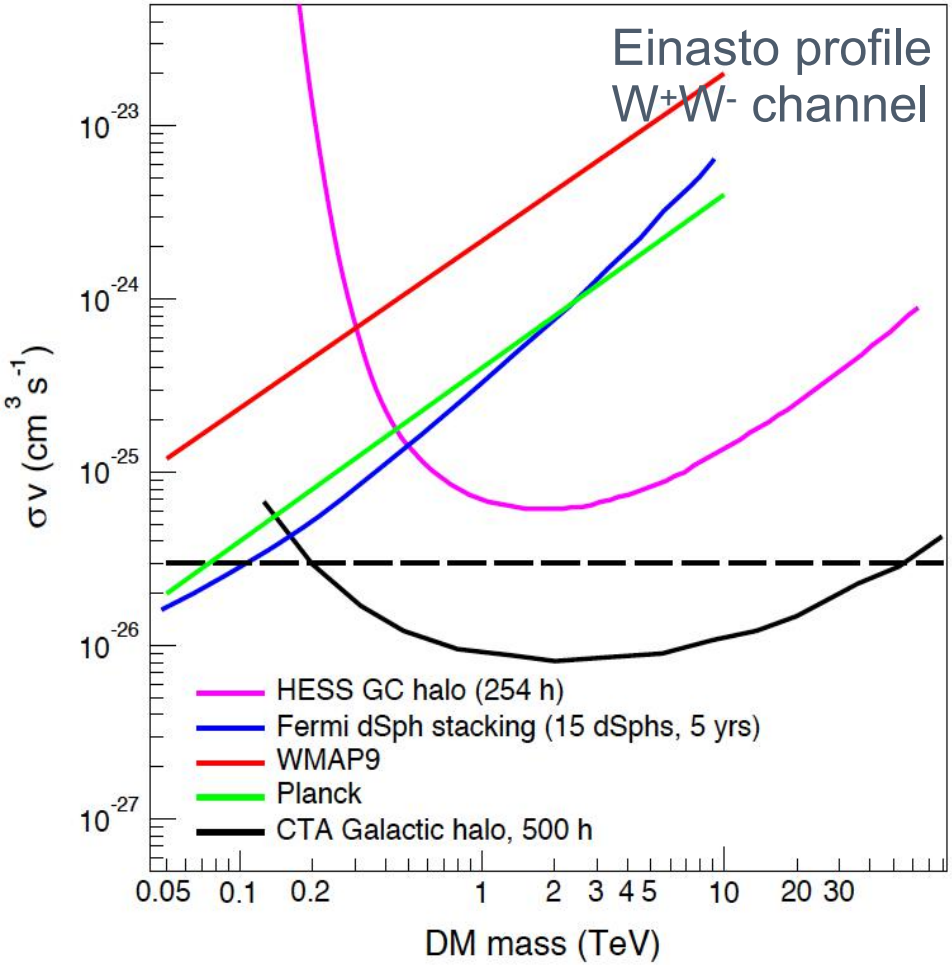
For the Einasto profile, strongest limits so far in the TeV mass range:

- in the WW channel: **6×10^{-26} cm^{-3} s^{-1}** at 1.5 TeV
- in the ττ channel: **2×10^{-26} cm^{-3} s^{-1}** at 800 GeV

Dark matter at the GC halo with CTA

- **Priority target in the CTA Dark Matter programme**
  - Fair balance between brightness and robustness





- **CTA is a unique player for TeV dark matter with great discovery possibility**